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Probabilistic Barge Impact Analysis of the Upper Guide and Guard Walls at Marmet Locks and Dam

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Final report

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Preface

This report describes the probabilistic barge impact analysis (PBIA) performed for the flexible design of the upper guide and guard walls at Marmet Locks and Dam on the Kanawha River. The funding for this research project was provided by U.S. Army Engineer District, Huntington. Mr. Michael Keathley, Design Branch, Structural Section, Huntington District, was the point of contact for this work effort.

The scale model experiments were performed at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, by Messrs. Ronald Wooley and Howard Park, Navigation Division, Coastal and Hydraulics Laboratory (CHL), under the direct supervision of Dr. Larry Daggett, Chief, Navigation Division, and under the general supervision of Dr. James R. Houston, former Director, CHL.

The PBIA and data processing were performed by Mr. Robert C. Patev, formerly of the Computer-Aided Engineering Division (CAED), Information Technology Laboratory (ITL), ERDC. Mr. Patev also compiled and wrote the report. This work was accomplished under the direct supervision of Mr. H. Wayne Jones, Chief, CAED, and under the general supervision of Mr. Timothy D. Ables, Acting Director, ITL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James S. Weller, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
kips (1,000 lbf)	4,448.222	newtons
pounds (force) per square inch	0.006894757	megapascals
square inches	0.00064516	square meters
tons (short)	907.1847	kilograms

1 Introduction

This report describes the development of a probabilistic barge impact analysis (PBIA) for the assessment of the flexible design guide and guard walls at Marmet Locks and Dam on the Kanawha River. The location of these walls at Marmet Lock is shown in Figure 1. The probabilistic definition of barge impact loads will assist with the design of the new approach walls adjacent to the existing dual 56-ft[1] lock chambers. The flexible design of the new walls was selected based on a screening study performed by INCA Engineers, Seattle, WA, that examined two different alternative foundation support systems. The final design selected for these walls consisted of a post-tensioned concrete box beam supported by a drilled shaft foundation support as shown in Figure 2.

The PBIA model was developed using the methodologies in ETL 1110-2-338[2] with some enhancements and modifications to the existing analytical model. The PBIA was performed using a Monte Carlo Simulation sampling method called Latin Hypercube that utilizes a stratified sampling technique. The PBIA simulations were executed using a commercially available computer program called @Risk for Microsoft Excel (Palisades Corporation, 1998). The number of iterations simulated for each PBIA and/or load case was 50,000 iterations (@Risk uses the term iterations instead of simulations). This was to ensure that the proper sampling was made to contain all statistical combinations of velocities, impact angles, and masses (tow distributions) as well as to ensure a sufficient probability density in the tails of the resulting distribution for impact forces.

The convergence of the resulting force distribution is based on the percentage change in the distribution moments (i.e., mean, standard deviation, and skewness) of the resulting distribution. The convergence criteria utilized for these analyses were a 0.01 percent change in each moment after each iteration. These convergence criteria are directly monitored by the @Risk program during the simulation run. The force distribution generally converged within

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[1] A table of factors for converting non-SI units of measurement to SI units can be found on page viii.

[2] U.S. Army Corps of Engineers. (1993). "Barge impact analysis," ETL 1110-2-338, Washington, DC.

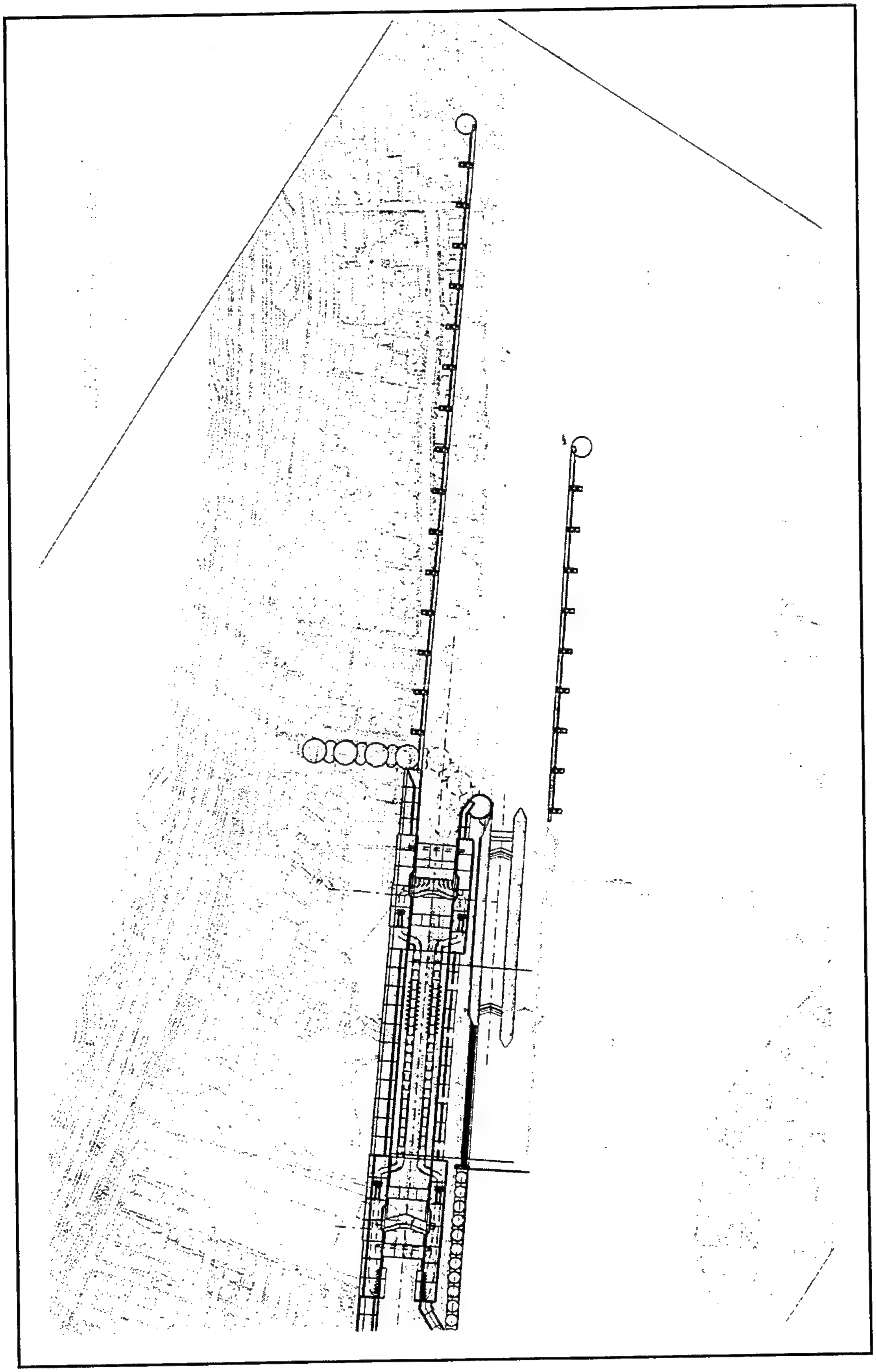

Figure 1. Layout of guide and guard walls at Marmet Lock

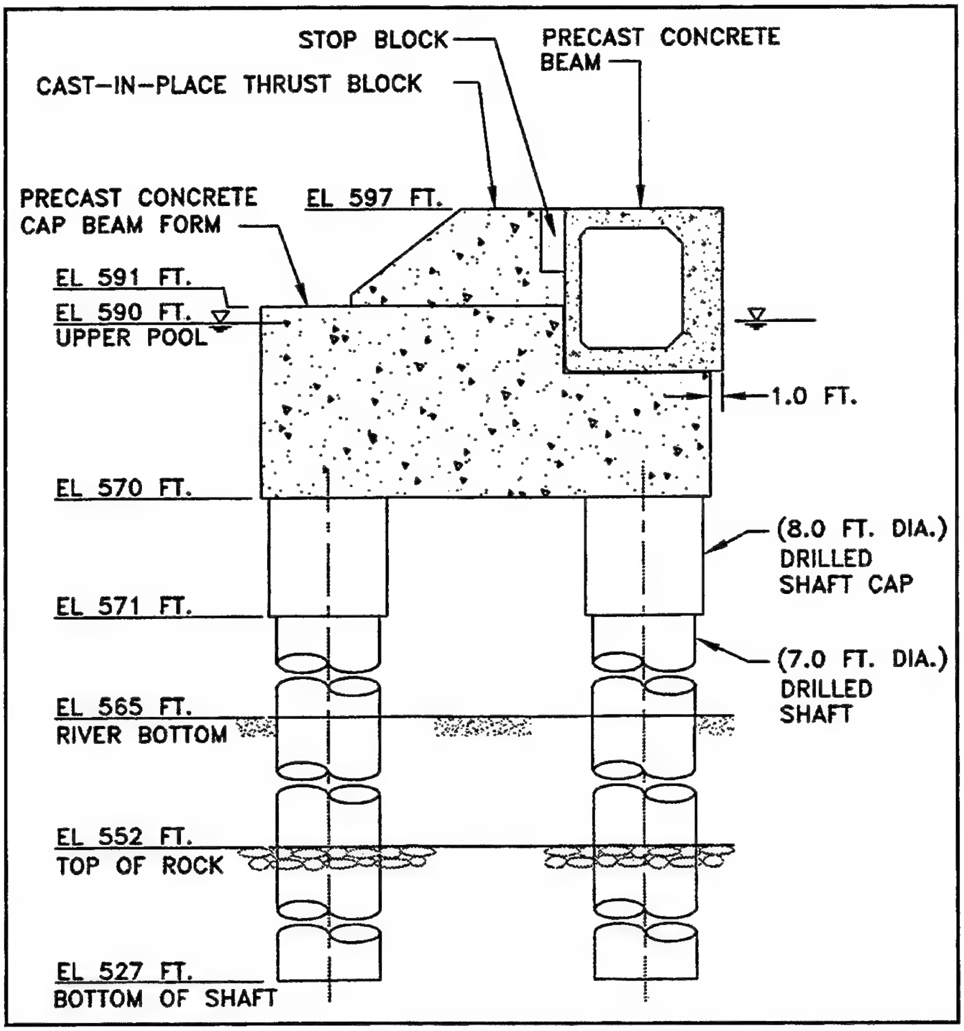

Figure 2. Flexible wall design for Marmet Locks and Dam

15,000 iterations; however, 50,000 iterations were run to permit the filling of the tails of the distribution. These distributions for impact forces were determined for individual impact events. These events are then annualized and assigned a probability for the hydraulic conditions in determining the return period for barge impact loads.

Chapter 2 of this report discusses the results from the 1:100 scale model experiments which are applicable to the design of the guide and guard walls. The data processing and statistical results are discussed for the riverflow events of 25,000- and 106,000-cfs controlled events and 50,000- and 125,000-cfs uncontrolled (loss of power) events.

Chapter 3 discusses the present and future tow and mass distributions for Marmet Locks and Dam, including tow beam and lengths used in the PBIA for standard and jumbo barges. Chapter 4 briefly discusses the development of return period scenarios for both approach walls at Marmet Locks and Dam. Chapter 5 presents the assumptions and constants used for the PBIA and the results from the PBIA for usual, unusual, and extreme load cases for both walls.

2 Results of Scale Model Experiments

Introduction

Scale model experiments were performed by the Coastal and Hydraulics Laboratory (CHL) at the Waterways Experiment Station (WES) to determine the approach velocities and angles of impact for both a nine-barge jumbo tow and an existing five-barge tow string. These experiments were laid out for various flow conditions to cover a range of hydraulic conditions as well as for the loss of power condition of a nine-barge tow. Overall, five-scale model testing sequences were recommended and documented. They are summarized and shown in Table 1.

Table 1
Summary of Model Experiments for Marmet Locks and Dam

Flow Condition, cfs	No. of Model Runs	Number of Barges	Controlled	Loss of Power	Walls Affected
25,000	25	9 (jumbos)	Yes	No	Guide wall
25,000	25	5 (standards)	Yes	No	Guard wall
50,000	25	9 (jumbos)	No	Yes	Guard wall/ Guide wall
106,000	25	9 (jumbos)	Yes (flanking)	No	Guide wall
125,000	25	9 (jumbos)	No	Yes	Guard wall

Barge impact experiments were conducted with the model simulating Plan B-1 conditions in the upper lock approach. The principal features of Plan B-1 for Marmet Locks and Dam are the existing features (items a-c) and the new features (items d-g):

a. Two locks with clear chamber dimensions of 56 ft wide by 360 ft long located along the right descending bank at about river mile 67.7.

b. A 557.5-ft-long gated spillway with five 100-ft-wide roller gates with crest elevation of 562.0 ft.[1]

c. A three-unit hydroelectric power plant located at the abutment end of the dam along the left bank.

d. A new lock with clear chamber dimensions of 110 ft wide by 800 ft long was located landward of the existing locks. The new lock is rotated 1 deg clockwise from parallel with the existing locks. The intersection of the center line of the upper gate pintle and the center line of the lock was located 163.5 ft landward of the center line of the landward existing lock at sta 1+22.0 A.

e. The forebay of the new lock was excavated to el 565.0 from the new guide wall riverward to the existing river channel and extended upstream to its convergence with the existing river channel about 3,000 ft upstream of the lock.

f. The new lock has a landside guide wall that extends upstream to sta 19+30 A using the new lock stations.

g. The upstream riverside guard wall of the riverward lock was removed from sta 0+95 to sta 4+55 and replaced with a 1,000-ft-long ported guard wall founded on 29.25-ft-diam cells spaced 105 ft apart. The guard wall had nine 75.75-ft-wide ports and ten 29.25-ft-diam cells. A 10-ft-wide by 8-ft-deep beam connected the cells and provided a rubbing surface for tows using the wall. A flow skirt extended down from the riverside of the beam to el 571.0 to control the flow moving through the port openings. The top of the guard wall was at el 595.0

Scale Model Experiment Procedures

The primary purpose of the experiments was to measure the velocities and angles of impact for a loaded barge that would assist in determining the impact forces that would be exerted on the new approach walls. These experiments covered usual operating events such as downbound approaches and abnormal or unusual events such as loss of power (LOP) during downbound approaches. Tow alignment, speed, and point of impact were measured using a video tracking system for each condition.

LOP experiments of tows entering the main lock chamber were conducted with a model tow representing a 9-barge tow drafting 9 ft with a 140-ft-long towboat. The tow represented a nine 35-ft-wide by 195-ft-long barge configuration 3 barges wide and 3 barges long for a total size of 105 ft wide by 725 ft long. Experiments of downbound tows using the existing locks were

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[1] All elevations (el) cited herein are in feet referenced to the National Geodetic Vertical Datum.

conducted with a tow representing a 5-barge single string of 35-ft-wide by 195-ft-long barges drafting 9 ft with a 140-ft-long towboat for a total length of 1,115 ft.

During the LOP experiments, the tow maneuvered under power to achieve the proper alignment with the main lock until it reached a point about two-tow lengths upstream of the upstream end of the guard wall. At that point, a loss of power was simulated by cutting all power to the engines and rudders. From that point to the point of impact no control or guidance was given the tow.

During normal approaches to the locks, the tow was under full control using reverse power and rudder controls, if and when necessary. This represents normal everyday traffic through the project.

Scale Model Experiment Results

The scale model experiment results are presented in Appendix A.

Experiment results for a downbound nine-barge tow approaching the main lock and LOP events are shown in Tables A-1 through A-4 and post-processed data are shown in Tables A-6 through A-9. The results for a five-standard-barge tow approaching the existing chambers are shown in Tables A-5 and A-10. The post-processed data include the velocities normal, V_n, and tangential, V_t, and rotation, ω, of the tow head with respect to the wall.

Nine-Jumbo-Barge Tow - LOP - 50,000 cfs

These results indicate that with a riverflow of 50,000 cfs and below, most of the tows experiencing LOP would hit either the main lock chamber or the existing locks. The impact location and usable experiments (i.e., those that did not have a 2 percent or greater error in forward or the local x-velocity of the barge) are shown in Table 2. Only 16 percent of the tows hit the new guard wall during a flow of 50,000 cfs, and the highest velocity of impact on the guard wall during the 50,000-cfs flow was 3.4 fps.

Table 2
Impact Location and Usable Experiments - Nine-Barge Tow Approaching Main Lock - Loss of Power - 50,000-cfs Riverflow

Impact Location	Number of Experiments	Usable Experiments
Hit center wall existing lock	4	3
Hit river wall main lock	11	11
Hit guard wall	4	4
Entered main lock chamber	4	4
Hit guide wall main lock	2	1
Total	25	23

Nine-Jumbo-Barge Tow - LOP - 125,000 cfs

With the 125,000-cfs riverflow, 60 percent of the tows experiencing LOP hit the new guard wall. The impact location and usable experiments are shown in Table 3. For the 125,000-cfs flow, the highest velocity of impact was 5.7 fps with an angle of impact of 38 deg. These velocities agree exactly with the flow velocity vectors in the area of the guard wall during the experiments.

Table 3
Impact Location and Usable Experiments - Nine-Barge Tow Approaching Main Lock - Loss of Power - 125,000-cfs Riverflow

Impact Location	Number of Experiments	Usable Experiments
Hit center wall existing lock	3	2
Hit river wall main lock	4	3
Hit guard wall	15	11
Entered main lock chamber	2	2
Hit upper end guide wall	1	0
Total	25	18

Nine-Jumbo-Barge Tow - 25,000 cfs

Experiments were conducted with a 9-barge tow maneuvering to enter the main lock chamber with 25,000- and 106,000-cfs riverflows. With the 25,000-cfs riverflow, a downbound tow could align with the landside guide wall, reduce speed, either land on the wall or drive close along the wall, and enter the main chamber without stopping. For the 25,000-cfs flow, the impact location and usable experiments are shown in Table 4.

Table 4
Impact Location and Usable Experiments - Nine-Barge Tow Approaching Main Lock - 25,000-cfs Riverflow

Impact Location	Number of Experiments	Usable Experiments
Head landed on guide wall	24	24
Enter into main lock/no impact	1	1
Total	25	25

Nine-Jumbo-Barge Tow Flanking - 106,000 cfs

With the 106,000-cfs flow, downbound tows are required to start a flanking maneuver about 3,000 ft upstream of the lock, move the tow into the right bank excavation, and approach the main lock at a safe speed. This flanking maneuver

requires the towboat to either move the head or the stern of the barges into the wall at some point. For the purposes of this PBIA, only the impacts of the tow with the head are utilized. The impacts with tow stern that are generally of less severity are ignored. For the 106,000-cfs flow, the impact location and usable experiments are shown in Table 5.

Table 5
Impact Location and Usable Experiments - Nine-Barge Tow Flanking into Main Lock - 106,000-cfs Riverflow

Impact Location	Number of Experiments	Usable Experiments
Head landed on guide wall	12	11
Stern landed on guide wall	13	0
Total	25	11

Five-Standard-Barge Tow - 25,000 cfs

Results of experiments with a downbound 5-standard-barge tow maneuvering to enter the existing locks with a riverflow of 25,000 cfs are shown in Table A5 and the processed results in Table A10. These data indicate the tow approaches and lands on the guard wall with the head of the tow every time except those tows that are able to enter directly. The speed of the tow reflects the low velocity of the currents acting on the tow as it approaches the existing locks. The impact location and usable experiments are shown in Table 6. The greatest velocity of impact was 2.6 fps and the maximum angle was 10.3 deg. The data show that nearly 68 percent of the tows landed on the wall with a velocity less than 1.0 fps.

Table 6
Impact Location and Usable Experiments - Five-Barge Single-String Tow Driving into Existing Locks - 25,000-cfs Riverflow

Impact Location	Number of Experiments	Usable Experiments
Head landed on guard wall	20	19
No impact on guard wall	5	5
Total	25	24

An additional note in working with the raw experiment data is that of the angles referenced to center line of existing locks - positive angle indicates head of tow rotated landward. The stations are measured from the center line of upper gate pintles of existing locks. Reference is made to the drawings for location of lights associated as shown in Appendix A, Figures A1-A5.

Processing of Raw Experiment Data

The raw data from the scale model experiments were processed using the rigid body motion of the tow using the velocities and angles of the two lights located on the tow as shown in Tables A1-A5. The assumption of using rigid body motion is proper for this analysis since the model barges and towboat are comprised of a single rigid system. There is no flexibility of the system accounted for in the model tow. In addition, the measurements are not taken at the point of impact but at some arbitrary point prior to impact of the guard wall. This point in the scale model is typically taken at around 5 to 10 ft from the wall. The reason for selecting this point is to try to eliminate scale model effects between the barge, water, and wall.

The processing of the raw experiment data takes the velocities and angles of the two strobe lights on the vessel and converts them to normal, tangential, and rotational components relative to the approach wall. The percentage of error is shown in the processing because it indicates that there was a difference in the local x-velocity (forward component in local barge coordinates). Since the scale model tow used for the experiments is a completely rigid body, there should be no difference in the local x-velocity components of the barge. Because this "stretching" cannot physically occur, the forward local x-component velocities must be the same between the lights. If the percentage error of the forward x-component is greater than 2 percent, processing error of the lights is assumed and the experiment is termed "unusable". The processed data are found in Appendix A. Tables A6-A9 show the processed data for the 25,000- and 106,000-cfs flow events, the 50,000-cfs LOP event, and the 125,000-cfs LOP event.

Development of Statistical Model Parameters

After the processing of the raw experiment data was performed for normal, tangential, and rotational components, the statistical parameters (means, standard deviations, and "best fit" probability distributions) were determined. The probability distributions were fitted and ranked using a computer program called BestFit. BestFit computes over 37 different discrete and continuous probability distributions, including extreme value distributions, and ranks them according to their statistics.

Since the experiment populations were relatively small (<30 usable experiments), the probability distributions were estimated, in most cases, on focusing toward the peak values and physical ranges of the experimental data rather than exact density fit. However, a probability distribution was not used that did not meet a majority of the statistical requirements. The distributions and associated statistical parameters used for each event in the PBIA are described in Table 7.

Table 7
Statistical Parameters and Distributions

Event		Distribution	Parameters (defined in @Risk)[1]
25,000-cfs 9-barge	V_t (ft/s) V_n (ft/s) Angle (deg)	Weibull Beta Beta	(1.23, 6.36) + -1.56-03 (0.78, 1.08)*2.43 + 1.48 (0.89, 1.06)*7.08 + 0.46
106,000-cfs flanking 9-barge	V_t (ft/s) V_n (ft/s) Angle (deg)	Uniform Triangular Triangular	Min= 0.11, Max = 0.89 (1.13, 2.60, 2.86) (1.00, 2.13, 6.00)
50,000-cfs 9-barge LOP	V_t (ft/s) V_n (ft/s) Angle (deg)	Normal Weibull Lognormal	$\mu = 1.04$ $\sigma = 0.26$ $\beta = 4.86$ $\alpha = 2.93$ $\mu = 10.87$ $\sigma = 1.97$
125,000 9-barge LOP	V_t (ft/s) V_n (ft/s) Angle (deg)	Normal Lognormal Triangular	$\mu = 4.63$ $\sigma = 0.95$ $\mu = 0.96$ $\sigma = 0.21$ $\mu = 5.10$ min = 0.0 max = 36
25,000-cfs 5-barge	V_t (ft/s) V_n (ft/s) Angle (deg)	Lognormal Lognormal Lognormal	$\mu = 0.94$ $\sigma = 0.40$ $\mu = 0.13$ $\sigma = 0.065$ $\mu = 6.92$ $\sigma = 1.47$

[1] μ = mean; σ = standard; α,β = Weibull parameters

Correlation of the data sets was also examined to see the importance of including them in the PBIA. Correlation can be ranked from values of -1 to +1, where zero has no correlation. It is recommended that a correlation value (positive or negative) of greater than 0.6 should be included into a Monte Carlo Simulation analysis. Hence, correlation was incorporated into the 25,000-cfs flow events for the PBIA. Table 8 shows the correlation values for the input random variable of normal and tangential velocities and impact angle. It is interesting to note that the correlation values of the random variables decrease as the flow event increases and with the loss of power.

Table 8
Correlation of Input Random Variables

Event	V_n vs V_t	V_n vs Angle	V_t vs Angle
25,000-cfs flow event – 9 barge	0.62478	0.73987	0.12987
106,000-cfs flow event – 9 barge	0.16349	0.30459	-0.18956
50,000-cfs LOP event	0.15467	0.45632	-0.14783
125,000-cfs LOP event	-0.15539	0.29504	-0.21362
25,000-cfs flow event	0.59996	0.67575	0.081972

3 Tow Distributions for Improved Fleet

Introduction

The distributions for the improved fleet anticipated at the new lock chamber at Marmet Locks and Dam are significantly different from past tow traffic patterns. Currently, the typical tow configuration is a 5-standard-barge string which can maneuver into the existing 56-ft by 360-ft twin chambers. In comparison, the projections for the improved fleet indicate that the typical barge approaching the new 110-ft by 800-ft lock chamber will be either a 9-barge jumbo tow or a 12-barge standard tow. Therefore, the probability distributions have been developed for both jumbo and standard tow configurations that will be utilizing the new lock chamber at Marmet Locks and Dam.

For the PBIA of the guard walls, the distributions and corresponding histograms for the improved fleet were invoked only for the 9-barge tow during the 25,000-cfs, 106,000-cfs flanking, and the 50,000- and 125,000-cfs LOP events. Since the guard wall will not be impacted during normal flow conditions, the PBIA for the 25,000-cfs 5-barge event did not use the distributions for the improved fleet and only utilized a single 5-standard-barge string in the analysis. Typically, the new guard will be utilized only during maintenance or emergency outages of the new lock chamber. In discussions with towing industry representatives, it was felt that during a maintenance closure of the new lock chamber at Marmet the industry would use only a five-barge jumbo string configuration.

Tow Distributions

The data for tow distributions for the improved fleet were supplied by the Navigation Data Center at the Huntington District, U.S. Army Corps of Engineers. The projections were made by each decade from the year 1990 for downbound tow quantities for both the projected jumbo and standard fleets. These distributions of tow size and quantities are shown in Tables 9 and 10. In addition, the probability of landing a loaded jumbo tow was assigned a value of

88.5 percent and the probability of landing a loaded standard tow was assigned a value of 11.5 percent. These probability distributions for the improved fleet are implemented as histograms within the PBIA for the 25,000-cfs, 106,000-cfs flanking, and the 50,000-cfs and 125,000-cfs LOP events.

Table 9
Projections for Downbound Tow Quantities of Loaded Jumbo Fleet (Improved Fleet)

		Quantity of Tows by Distributions for Projected Year and Quantity						
Barges per Tow	Distribution of Tow Size	1990 8,104 Jumbos	2000 10,736 Jumbos	2010 12,492 Jumbos	2020 14,570 Jumbos	2030 16,587 Jumbos	2040 18,799 Jumbos	2050 20,454 Jumbos
1	0.003	24.3	32.2	37.5	43.7	49.8	56.4	61.4
2	0.006	24.3	32.2	37.5	43.7	49.8	56.4	61.4
3	0.055	148.6	196.8	229.0	267.1	304.1	344.6	375.0
4	0.018	36.5	48.3	56.2	65.6	74.6	84.6	92.0
5	0.024	38.9	51.5	60.0	69.9	79.6	90.2	98.2
6	0.084	113.5	150.3	174.9	204.0	232.2	263.2	286.4
7	0.028	32.4	42.9	50.0	58.3	66.3	75.2	81.8
8	0.034	34.4	45.6	53.1	61.9	70.5	79.9	86.9
9	0.704	633.9	839.8	977.2	1139.7	1297.5	1470.5	1600.0
10	0.020	16.2	21.5	25.0	29.1	33.2	37.6	40.9
11	0.022	16.2	21.5	25.0	29.1	33.2	37.6	40.9
Totals	1.000	1119.2	1482.7	1725.2	2012.2	2290.8	2596.2	2824.25

Waterborne Commerce Data

Since the reported tow tonnage data from the Lock Performance Monitoring System (LPMS) are very inconsistent, the statistics from Waterborne Commerce (WBC) Data for the years of 1993-1997 at Marmet Locks and Dam were analyzed to determine the representative tonnage per barge of tows transiting the lock. The tonnage data input into WBC are usually quite accurate and are taken directly from the manifest record onboard the vessel. The WBC data have been analyzed to develop average weights versus the lengths and average width (beam) of the barge for use in the PBIA. Summaries of the WBC data are shown in Tables 11 (1993-1995) and 12 (1996-1997).

From the data, the average weight for a jumbo barge was determined to be about 1,532 short tons and for a standard barge around 980 short tons. The coefficient of variation (standard deviation divided by mean) for the weights ranged from 3 to 7 percent. This variation in the barge mass was incorporated into the PBIA. In addition, since the WBC data are typically used for economic purposes, the data do not include the tare weight for the barges. These tare

Table 10
Projections for Downbound Tow Quantities of Loaded Standard Fleet (Improved Fleet)

		Quantity of Tows by Distributions for Projected Year and Quantity						
Barges per Tow	Distribution of Tow Size	1990 1,441 Stands.	2000 1,911 Stands.	2010 2,224 Stands.	2020 2,595 Stands.	2030 2,954 Stands.	2040 3,349 Stands.	2050 3,644 Stands.
1	0.001	1.4	1.9	2.2	2.6	3.0	3.3	3.6
2	0.002	1.4	1.9	2.2	2.6	3.0	3.3	3.6
3	0.007	3.4	4.5	5.2	6.1	6.9	7.8	8.5
4	0.035	12.6	16.7	19.5	22.7	25.8	29.3	31.9
5	0.009	2.6	3.4	4.0	4.7	5.3	6.0	6.6
6	0.021	5.0	6.7	7.8	9.1	10.3	11.7	12.8
7	0.006	1.2	1.6	1.9	2.2	2.5	2.9	3.1
8	0.080	14.4	19.1	22.2	26.0	29.5	33.5	36.4
9	0.079	12.6	16.8	19.5	22.8	25.9	29.4	32.0
10	0.017	2.4	3.2	3.8	4.4	5.0	5.7	6.2
11	0.038	5.0	6.6	7.7	9.0	10.2	11.6	12.6
12	0.598	71.8	95.2	110.8	129.3	147.2	166.9	181.6
13	0.051	5.7	7.5	8.7	10.2	11.6	13.1	14.3
14	0.055	5.7	7.5	8.7	10.2	11.6	13.2	14.3
Totals	1.000	145.3	192.7	224.3	261.7	297.9	337.8	367.5

Table 11
Waterborne Commerce Data - 1993-1995

Lengths, ft	Number of Barges	Avg. Width, ft	Avg. Weight, short tons	% of Tows	Displacement, short tons (assume draft 9 ft)
>200	2	44.50	2738.50	0.02%	
200	1278	35.02	1614.19	12.02%	1969.85
195 total	6742	33.67	1467.65	63.39%	1846.47
195	5744	35.00	1529.93	54.01%	1919.53
195	998	26.00	1109.21	9.38%	1425.94
187	119	35.00	1531.91	1.12%	1840.78
175	2494	26.00	970.28	23.45%	1279.71
Total	10635			100.00%	

Table 12 Waterborne Commerce Data - 1996-1997					
Lengths, ft	Number of Barges	Avg. Width, ft	Avg. Weight, short tons	% of Tows	Displacement, short tons (assume draft 9 ft)
>200	1	38.00	1100.00	0.01%	
200	1389	34.98	1584.05	12.06%	1967.74
195 total	7102	34.15	1491.71	61.64%	1872.90
195	6431	35.00	1532.12	55.81%	1919.53
195	671	26.00	1104.44	5.82%	1425.94
187	0				
175	3030	26.00	986.97	26.30%	1279.69
Total	11522			100.00%	

weights as well as a towboat weight of 508 short tons were added to the values for tow mass after each iteration of tow mass in the PBIA. This permits the PBIA not to include any variation in the tare weight of the barge and weight of the towboat.

Tow Lengths and Widths

The tow lengths and widths are necessary in the PBIA model to determine the center of gravity and inertial components of the barge. The lengths and widths of the improved fleet are determined for the full range of possible configurations for both jumbo and standard barges. The towboat was assumed to have a constant value of 125 ft in length and 26 feet in width, with 5 ft of draft. The tow lengths and widths incorporated in PBIA for Marmet are shown in Table 13.

Table 13
Tow Lengths and Widths for PBIA Input

Barges in Tow	Jumbo Tows		Standard Tows	
	Length	Width	Length	Width
1	320	35	300	26
2	515	35	475	26
3	710	35	650	26
4	515	70	475	52
5	585	70	525	52
6	710	70	650	52
7	780	70	700	52
8	585	105	525	78
9	710	105	650	78
10	780	105	700	78
11	780	105	700	78
12	-	-	650	104
13	-	-	700	104
14	-	-	700	104

4 Development of Return Period Scenarios

Upper Guard Wall

Introduction

The development of return periods is based on the load cases selected for the upper guard wall at Marmet Locks and Dam. The load cases examined for this report are usual, unusual, and extreme. The usual load case assumes the structure to stay in the elastic range and that no damage other than cosmetic occurs to the structure. The unusual load case assumes some nonlinear behavior and that there is some minor damage that can be repaired in the future. The extreme load case assumes that damage is heavy and that emergency repairs will be required.

The design values for barge impact forces will be based on logical reasoning and various scenarios developed for the return periods of each load case. As explained below, the new guard wall at Marmet Locks and Dam is not atypical of Corps navigation structures.

Usual Load Case

The usual load case is not typical for this type of navigation structure, especially for a guard wall. The scale model experiments indicate that no tows will impact the wall unless the riverflows exceed 50,000 cfs. Unfortunately, this is only true for the LOP events because even under the 106,000-cfs controlled flanking experiments (Table 1), no impacts occurred on the guard wall. Therefore, the usual load case assumes that no tows impact the guard wall during the life of the structure. Thus, the return period defined for this event is zero.

Unusual Load Case

As discussed in the previous chapter, the unusual loading case considers the use of the new guard wall during either scheduled maintenance or emergency closure of the new lock chamber. In discussions with Huntington District Operations and Maintenance personnel, maintenance events will occur in an exposure time of once in every 10 years. The closure during the maintenance condition would be approximately 6 weeks of interruption to traffic flows. During this closure time, it was estimated that approximately 120 tows per week, or 720 tows, would approach the new guard wall. As discussed in the previous chapter the tows that approach the new guard wall to utilize the 56-ft chambers would be a 5-jumbo-barge string.

In addition, the planned closures for these maintenance events could only occur during lower flows which would be typically less than 50,000 cfs. Therefore, in the PBIA, the LOP events were not applicable to this load case. So only 25,000-cfs experiment data for the 5-standard-barge string were utilized to determine the barge impact force distribution and return period. Typically, a return period of 50 to 100 years would be selected for the unusual load case. However, the values of 150 and 200 years for the beam and foundation, respectively, were selected to account for potential variations in the duration due to emergency closures.

Extreme Load Case

The extreme load case is highly dependent upon the LOP events. Since the guard wall only saw barge impacts during the 50,000- and 125,000-cfs LOP events, the data from these experiments were combined and used in the PBIA. The data from the other scale model experiments were inappropriate to use for this load case. In hindsight, other experiments could have been selected, such as controlled approaches to the existing chambers under high flow events.

However, the problem with return period arises because the probability of occurrence for an LOP event is exceedingly small. The probabilities for LOP events range from 10^{-6} to 10^{-7}. Compounding the problem is the annual probability of exceedence flows at Marmet Locks and Dam. The annual probabilities of flow exceedence are 0.03 for a 50,000-cfs event and 0.01 for a 125,000-cfs event.

For the return periods for the extreme load case, only the values for the flow exceedence probabilities were used to determine the return period for barge impact loads. Using these probability values singly and ignoring the LOP probabilities will lead to a relatively conservative design value for the extreme load case impact force. This is because a tow with full power during an extremely high flow event would still be subjected to high flow velocities, and hence the tow would probably still have minimal control. These assumptions were verified by reviewing the flow vectors during the scale model experiments. The velocity of the tow and the flow vectors in the area of the upper approach

were very nearly the same. These data permit the upper bound for barge impact force and permit the PBIA to perform an extreme value analysis.

Return Periods

The return periods, presented in Table 14, for the new guard wall at Marmet Locks and Dam were selected based on the logical reasoning and discussions above. As stated earlier, this is atypical for previous PBIAs performed for other Corps navigation approach structures. In addition, return periods are developed for both the foundation (drilled shafts with cap) and the post-tensioned box beam because the foundation is a more critical element of the guard wall than the box beam. The values used for the return periods for the foundation and midspan of the post-tensioned beam are shown in Table 14.

Table 14
Return Period for Event Scenarios for Upper Guard Wall at Marmet Locks and Dam

	Usual	Unusual	Extreme
Foundation	0	200	1,000
Beam	0	150	500

Upper Guide Wall

Introduction

The development of return periods and load cases for the upper guide wall is based on different criteria than for the upper guard wall at Marmet Locks and Dam. The upper guide wall will only receive barge impact forces during normal approaches to the guide wall. These impact load cases can be expected during periods of normal downbound traffic movement. These impacts can also be anticipated during both normal and high riverflows as indicated by the selected model experiments for the 25,000- and 106,000-cfs events.

In addition, the results from the scale model experiments indicate that the LOP events will not affect the upper guide wall. This is because the flow vectors (at 50,000- and 125,000-cfs) are directed away from the guide wall and toward the upper guard wall and dam. Also, the LOP event has an annual probability equal to approximately 1×10^{-6}. Since this analysis does not incorporate extreme value modeling like the upper guard wall, it would have minimal effect on the final impact force distribution. Hence these LOP events were not simulated into the PBIA for the upper guide wall. However, to ensure proper results, sensitivity analyses were executed, and the final results were considered negligible.

The return periods from the PBIA have been developed for the usual, unusual, and extreme cases. The usual load case assumes the structure to stay in the elastic range and that no damage other than cosmetic occurs to the structure. The unusual load case assumes some nonlinear behavior and that there is some minor damage that can be repaired in the future. The extreme load case assumes that damage is heavy and emergency repairs will be required.

Return Periods

The following return periods for the new guide wall at Marmet Locks and Dam were selected based on the discussions above. As stated earlier, these return periods are considered rational based on the upper guard wall and other PBIAs performed on Corps of Engineers navigation approach structures. In addition, return periods are developed for both the foundation (drilled shafts with cap) and post-tensioned box beam. These return periods are different for each element of the upper guard wall because the foundation is considered a more critical component of the guard wall system than the box beam. The values used for the return periods for the foundation and midspan of the post-tensioned beam are shown in Table 15.

Table 15
Return Period for Event Scenarios for Upper Guide Wall at Marmet Locks and Dam

	Usual	Unusual	Extreme
Foundation	5	200	1,000
Beam	5	150	500

5 Probabilistic Barge Impact Analysis

Upper Guard Wall

Introduction

The PBIA was performed on both the design of the foundation support (drilled shafts with cap) and the midspan of the post-tensioned concrete box beam. The structures were both considered to be flexible structures and not rigid. This requires the calculation of stiffness for each of the systems. However, the stiffness was not considered a random variable in the PBIA, even though the unit weight of concrete and compressive strength are truly not deterministic. In addition, the input random variables and model constants are described and any assumptions made in the PBIA are discussed. The final results for barge impact force are presented, based on return periods for each load case of usual, unusual, and extreme.

Foundation

Stiffness. The stiffness for the drilled shaft and concrete cap foundation shown in Figure 1 is determined assuming a fixed-fixed beam calculation. The equation for stiffness for this case is $3EI/L^3$. Using this equation tends to lead to a slightly conservative value for the system stiffness since the ends of the drilled shaft (at the cap and rock) do have some rotation to them. The modulus of elasticity was calculated using the ACI equations relating it to compressive strength. Also, for simplicity, the diameter of the shafts is considered to be 7 ft for the full length, and the length of the shaft was approximated as 25 ft to account for approximated soil /rock interaction. The parameters for the concrete drilled shafts are;

Unit weight	150 pcf
Compressive strength	4,000 psi
Modulus of elasticity (ACI equation)	3,834,254 psi

The stiffness calculated for the foundation is approximately 25,000 k/ft. This means that for a impact load of 680 kips, 0.0136 ft, or 0.163 in., of deflection would be expected. This corresponds very well to the results from the finite element analysis (FEA) performed by INCA Engineers during the Alternative Screening Phase of Marmet Locks and Dam. However, it should be noted that this PBIA model does not modify this stiffness value to account for the inelastic behavior or the cracking of the concrete.

Input PBIA parameters. The input random variable and constants used in the PBIA for the foundation are defined in Table 16. The statistical values and distributions for the random variables (i.e., velocity, angle, and mass) are discussed in previous chapters. The constants are discussed here to document the complete input for the PBIA. Some of these constants (i.e., Minorsky coefficient, unit weight of concrete, etc.) should have been considered random variables in the PBIA. However, these were eliminated because of the limited availability of statistical data and distribution as well as their limited sensitivity to the PBIA results.

Table 16
Random Variables and Constants in the PBIA for the Foundation

Variables	
Velocities (normal and tangential)	
Impact angle	
Mass (tow distribution)	
Constants	
Stiffness	24,988.29 k/ft
Added mass constant	1.4
Effective plate thickness	1.17 in.
Friction coefficient	0.18
Minorsky pressure constant	13.7 psi

Results. The PBIA results for all three load cases are shown in Table 17. Figures 3 and 4 show the plots of return period versus impact load for the foundation. Return periods given for the extreme events are shown for each decade. This accounts for the projected increase in tow traffic and the change of the improved tow fleet over the next 50 years.

Midspan of beam

Stiffness. The stiffness of the post-tensioned box beam cannot be determined using simple beam equations because of the need to account for the post-tensioning force applied within the beam. For this PBIA, the results from an FEA were utilized. The FEA was performed by INCA Engineers and was

Table 17 PBIA Impact Forces and Return Periods for the Foundation - Upper Guard Wall				
	Usual	Unusual	Extreme	
Return period, years	0	200	1000	
Impact force, kips	0	250	Year	Force
			2000	1060
			2010	1080
			2020	1103
			2030	1124
			2040	1138
			2050	1149

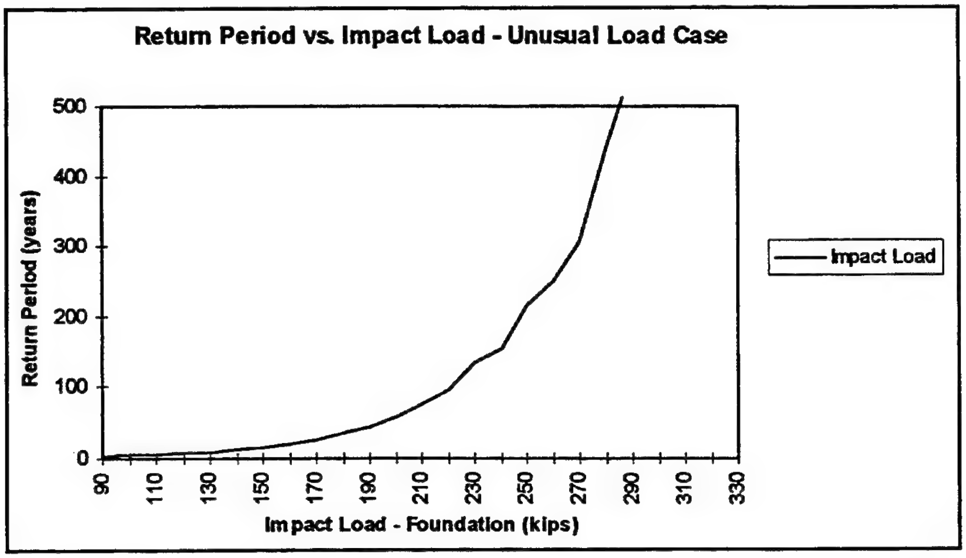

Figure 3. Unusual load case - return period and impact load for foundation at Marmet Locks and Dam - upper guard wall

calculated based on a 680-kip load at the midspan of the beam. Results from the FEA showed that the stiffness at the midspan was approximately 14,470 k/ft. This was based on the relative deflections at the midspan of the beam and at the point halfway from the end foundation support. As in the foundation model, no variability in stiffness was accounted for in the PBIA.

Input PBIA parameters. The input random variables and constants used in the PBIA for the midspan of beam are defined in Table 18. The statistical values and distributions for the random variables (i.e., velocity, angle, and mass) are discussed in previous chapters. The constants are discussed here to document the complete input for the PBIA. Some of these constants (i.e., Minorsky

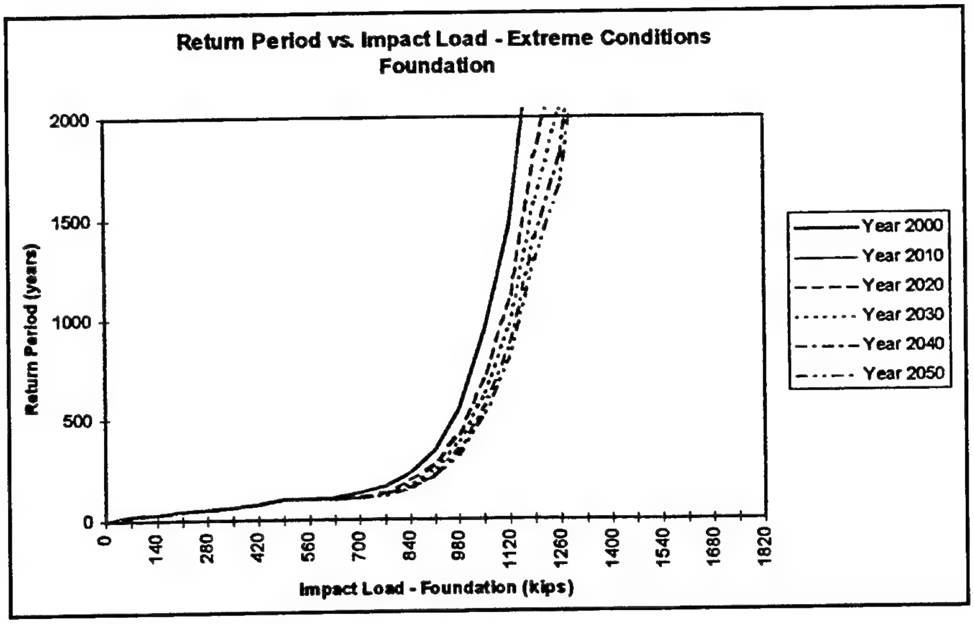

Figure 4. Extreme load case - return period and impact load for foundation at Marmet Locks and Dam - upper guard wall

Table 18 **Random Variables and Constants in the PBIA for the Midspan of Beam**	
Random Variables	
Velocities (normal and tangential)	
Impact angle	
Mass (tow distribution)	
Constants	
Stiffness	14,470 k/ft
Added mass constant	1.4
Effective plate thickness	1.17 in.
Friction coefficient	0.18
Minorsky pressure constant	13.7 psi

coefficient, unit weight of concrete, etc.) should have been considered random variables in the PBIA. However, these were eliminated because of the limited availability of statistical data and distribution as well as their limited sensitivity to the PBIA results.

Results. The PBIA results are shown for all three load cases in Table 19. Figures 5 and 6 show the plots of return period versus impact load for the midspan of beam. Return periods given for the extreme events are shown for

Table 19
PBIA Impact Forces and Return Periods for the Midspan of Beam - Upper Guard Wall

	Usual	Unusual	Extreme	
Return period, years	0	150	500	
Impact force, kips	0	295	Year	Force
			2000	943
			2010	972
			2020	1006
			2030	1027
			2040	1056
			2050	1078

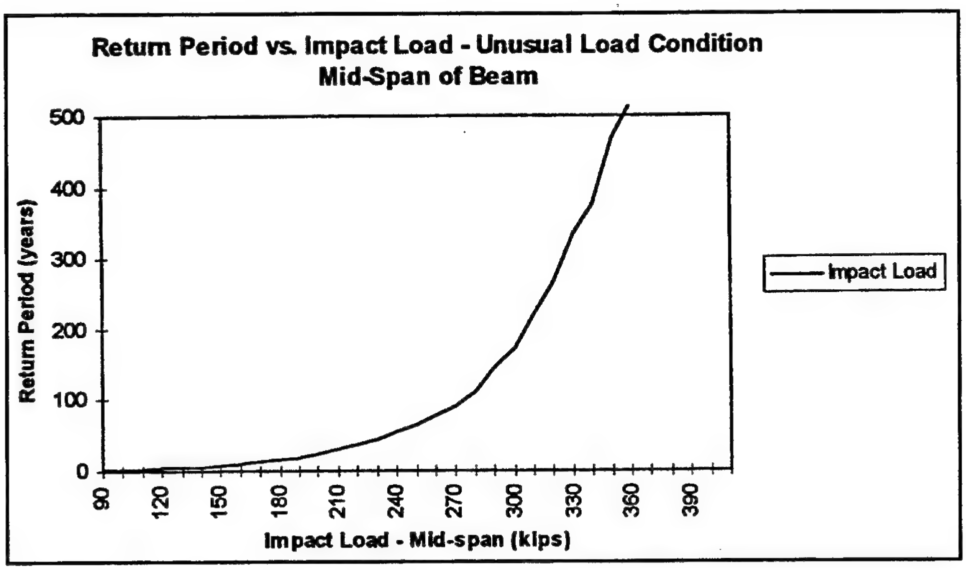

Figure 5. Unusual load case - return period and impact loads for midspan of beam at Marmet Locks and Dam - upper guard wall

each decade. This accounts for the projected increase in tow traffic and the change of the improved tow fleet over the next 50 years.

Also, there is a slight difference in the results from the foundation to midspan for the various return periods. This difference can be justified because while the midspan is more flexible than the foundation section, an impact at midspan requires additional mass be added from the other foundation support and beam. Hence, there is this tradeoff between the stiffness and mass for the foundation and midspan components. In this case, the mass created a slight increase in the impact force for the midspan PBIA.

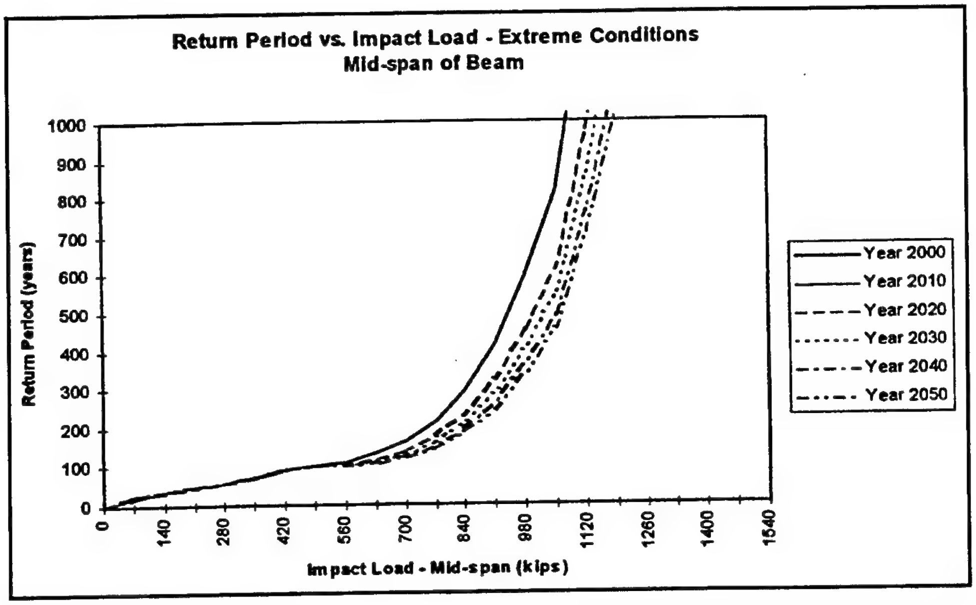

Figure 6. Extreme load case - return period and impact loads for midspan of beam at Marmet Locks and Dam - upper guard wall

Upper Guide Wall

Introduction

The PBIA for the upper guide wall utilized the similar input probabilistic parameters as discussed in the previous sections for the upper guard wall. This is because at the time of this analysis both approach walls are to be of a similar size and design that would use a post-tensioned beam with drilled shaft foundation. Therefore, the stiffness values for the upper guide wall are the same as for the upper guard wall design. Also, like the upper guard wall, the PBIA results for the upper guide wall have been reported for both the foundation and beam elements of the wall.

Input PBIA Parameters

The statistical values and distributions for the random variables for the upper guide wall (i.e., velocity, angle, and mass) were discussed in Chapters 2 and 3. The PBIA for the upper guide wall utilizes the processed distributions for the velocities and angles from 25,000-cfs nine-jumbo tow and the 50,000-cfs nine-jumbo. The projected traffic distributions for Marmet (discussed in Chapter 3) are invoked into the model to account for both jumbo and standard barge configurations. The constants used in the PBIA for the upper guide wall were defined in Table 18. Some of these constants (i.e., Minorsky coefficient, unit weight of concrete, etc..) should have been considered random variables in the PBIA. However, these were eliminated due to the limited availability of

statistical data and distributions as well as their limited sensitivity to the PBIA results.

Results

The PBIA was performed for the foundation and midspan sections of the upper guide wall at Marmet Locks and Dam. This set of analyses assumes the same post-tensioned box beam and drilled shaft foundation as the upper guard wall PBIA discussed in the previous chapter. The barge impact forces normal to the wall were determined for an annualized probability of exceedence based on 2,300 lockages per year. The cumulative annualized probabilities were fit to a Type II asymptotic largest value cumulative distribution function (CDF). The equation for the CDF for the Type II extreme value distribution, Fs(F), is

$$F_s(F) = \exp\left[-\left(\frac{F_n}{F}\right)^k\right]$$

where $F_s(F)$ is the cumulative probability (annual), F is force of interest, F_n is the force corresponding to the standard variate, s, s = 0 (i.e., $F_s(F) = e^{-1} = 0.3876$), and k is the shape parameter or slope of Type II largest type CDF which is represented by

$$k = \frac{s}{\ln F - \ln F_n}$$

The return periods were determined using the same design values determined for the upper guide wall analysis. The return periods were calculated based on the reciprocal of the annual cumulative probability for the Type II largest values. The PBIA results for the upper guide wall at are shown in Table 20.

Table 20
PBIA Impact Forces (Normal to Wall) and Return Periods for Upper Guide Wall

	Foundation		Midspan	
Load Case	Return Period, years	Force, kips	Return Period, years	Force, kips
Usual	5	370	5	350
Unusual	200	640	150	600
Extreme	1000	810	500	710

PBIA for Upper Guide Wall Protection Cell

Currently there are no existing analytical models or guidance based on the head-on impact of a barge into a cellular protection cell. These impacts are a highly nonlinear event in terms of both the barge and wall system. The existing barge impact model defined in ETL 1110-2-338[1] tries to account for the permanent deformation (i.e., nonlinearity) of the barge corner or headlog through the use of the Minorsky's coefficient. However, the equations for the single-degree-of-freedom (SDOF) stiffness term are based on a tangent function that includes the angle of impact and the Minorsky's coefficient, P_m. This equation in its current form is not very well suited to predicting reasonable impact forces for head-on collisions. This is especially true for angles of impact greater than 75 deg or less than 2 deg. Because of these factors, the PBIA model for the protection cell will not be discussed in this report.

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[1] U.S. Army Corps of Engineers. (1993). "Barge impact analysis," ETL 1110-2-338, Washington, DC.

Appendix A
Scale Model Experiment Results

Table A1
Nine-Barge Tow Approaching Main Lock - 25,000-cfs Riverflow

Impact Area or Station	Bow Light Angle, deg	Bow Light Speed, fps	Stern Light Angle, deg	Stern Light Speed, fps	Angle of Tow, deg	Remarks
Sta 1583	4.6	3.7	4.6	3.4	3.1	Head landed on guide wall
Sta 1583	4.6	3.1	13.5	3.2	4.4	Head landed on guide wall
Sta 1634	4.6	3.7	9.1	4.0	2.6	Head landed on guide wall
Sta 1487	2.3	2.8	13.5	2.7	7.1	Head landed on guide wall
Sta 1536	0	2.7	4.6	2.4	6.7	Head landed on guide wall
Sta 1380	4.6	3.9	4.6	4.1	5.8	Head landed on guide wall
Sta 1132	0	3.0	2.3	3.0	4.5	Head landed on guide wall
Sta 1082	2.3	2.4	2.3	2.3	2.1	Head landed on guide wall
Sta 1085	2.3	2.5	0.5	2.8	4.2	Head landed on guide wall
Sta 1098	6.8	3.8	4.6	4.0	3.8	Head landed on guide wall
Sta 684	2.3	2.2	9.1	2.2	2.1	Head landed on guide wall
Sta 1484	2.3	1.8	0	2.0	7.5	Head landed on guide wall
Sta 784	2.3	2.5	0	2.4	1.0	Head landed on guide wall
Sta 260	2.3	1.5	0	1.5	0.5	Head landed on guide wall
Sta 735	-2.3	1.7	2.3	1.9	1.8	Head landed on guide wall
Sta 1721	4.6	2.4	2.3	2.6	4.7	Head landed on guide wall
Sta 1235	0.8	1.9	4.6	2.0	6.6	Head landed on guide wall
Sta 1207	-2.5	2.5	4.6	2.4	1.7	Head landed on guide wall
Sta 1160	2.3	1.9	0	1.8	5.1	Head landed on guide wall
					1.1	Tow entered main lock / no impact on walls
Sta 1031	0	2.1	2.3	2.1	3.6	Head landed on guide wall
Sta 410	-2.3	2.0	0	2.5	2.3	Head landed on guide wall
Sta 1534	2.3	1.7	2.3	1.6	4.3	Head landed on guide wall
Sta 586	9.1	1.9	0	1.9	1.0	Head landed on guide wall
Sta 1561	0	2.3	0	1.9	4.7	Head landed on guide wall

Table A2
Nine-Barge Tow Flanking - 106,000-cfs Riverflow

Impact Area or Station	Bow Light		Stern Light		Angle of Tow, deg	Remarks
	Angle, deg	Speed, fps	Angle, deg	Speed, fps		
Sta 1835	9.1	1.6	6.8	1.6	-3.4	Stern landed on guide wall
Sta 1710	-2.3	0.9	13.5	0.6	-4.3	Stern landed on guide wall
Sta 1780	-26.6	2.2	34.2	3.0	-14.0	Stern landed on guide wall
Sta 1810	-6.8	2.0	6.8	1.8	-3.6	Stern landed on guide wall
Sta 1604	13.5	1.9	9.1	0.8	-4.6	Stern landed on guide wall
Sta 1330	9.1	2.6	0	1.5	2.3	Head landed on guide wall
Sta 1811	-9.1	9.8	13.5	0.8	-3.2	Stern landed on guide wall
Sta 1310	11.3	2.4	-6.8	2.3	2.6	Head landed on guide wall
Sta 1859	6.8	1.8	-6.8	1.6	-0.4	Stern landed on guide wall
Sta 1561	4.6	1.9	0	1.9	-4.0	Stern landed on guide wall
Sta 1454	2.3	2.7	-2.3	2.5	3.2	Head landed on guide wall
Sta 360	2.3	2.6	-6.6	3.3	6.0	Head landed on guide wall
Sta 1610	4.6	2.8	-6.8	2.6	3.3	Head landed on guide wall
Sta 1835	-9.1	1.0	0	1.6	-1.1	Stern landed on guide wall
Sta 1260	4.6	2.7	0	2.6	2.4	Head landed on guide wall
Sta 1800	4.6	1.4	2.23	1.4	-0.2	Stern landed on guide wall
Sta 1510	27.5	1.8	-15.6	1.6	1.7	Head landed on guide wall
Sta 1585	23.7	1.3	-23.7	1.3	2.2	Head landed on guide wall
Sta 1360	11.3	2.2	-6.8	2.2	2.1	Head landed on guide wall
Sta 1780	-6.8	1.4	4.68	1.6	-0.6	Stern landed on guide wall
Sta 1535	17.7	2.8	-22.2	2.5	1.7	Head landed on guide wall
Sta 1585	-15.6	2.0	11.3	2.0	-2.1	Stern landed on guide wall
Sta 1433	31.0	1.7	-15.6	1.5	2.5	Head landed on guide wall
Sta 1909	4.6	2.1	4.6	2.1	-0.9	Stern landed on guide wall
Sta 1435	17.7	1.7	-6.8	1.6	1.9	Head landed on guide wall

Table A3
Nine-Barge String Approaching Main Lock - Loss of Power - 50,000-cfs Riverflow

Impact Area or Station	Bow Light		Stern Light		Angle of Tow, deg	Remarks
	Angle, deg	Speed, fps	Angle, deg	Speed, fps		
Sta 649	-6.8	3.8	-6.8	3.4	-13.7	Hit guard wall
	-9.5	2.8	-2.3	5.0	-7.7	Hit center wall existing locks
	-6.8	2.1	0	2.2	-11.8	Hit riverwall main lock
	9.1	4.2	2.3	4.2	9.1	Hit main lock chamber
	0	3.8	-6.8	3.5	-0.4	Hit riverwall main lock
	6.8	1.8	2.3	1.7	4.4	Hit main lock chamber
	-6.8	2.8	-2.3	2.9	-2.0	Hit riverwall main lock
	-13.5	2.5	10.0	2.5	-6.2	Hit riverwall main lock
	-4.6	2.0	-6.8	2.1	-1.0	Hit riverwall main lock
Sta 310	-8.1	2.6	-11.3	2.5	-11.7	Hit guard wall
	-11.3	2.6	-11.3	2.7	-14.6	Hit center wall existing locks
	-4.6	2.7	-6.8	3.2	-15.9	Hit center wall existing locks
	-6.8	2.6	-6.8	2.7	-6.4	Hit center wall existing locks
	-9.1	2.1	-4.6	2.1	-3.1	Hit riverwall main lock
	-5.2	1.1	0	1.1	-2.6	Hit riverwall main lock
Sta 587	-13.5	3.1	-11.3	2.7	-8.7	Hit guard wall
Sta 661	-13.5	2.0	-11.3	2.6	-9.4	Hit guard wall
	6.8	2.7	-2.3	2.8	6.2	Hit riverwall main lock
Sta 941	2.3	0.3	4.6	2.6	6.7	Hit guide wall main lock
	-6.8	2.9	-4.6	2.8	-3.7	Hit riverwall main lock
	-2.3	2.6	-4.6	2.6	-2.9	Hit riverwall main lock
	-3.5	2.3	-3.6	2.5	-3.7	Hit riverwall main lock
	-0.1	0.8	0	0.9	-0.2	Entered main lock chamber
	0	1.0	0	1.0	-0.3	Entered main lock chamber
	1.0	4.2	0.9	4.2	1.0	Hit upstream end of main lock guide wall

Table A4
Nine-Barge Tow Approaching Main Lock - 125,000-cfs Riverflow

Impact Area or Station	Bow Light		Stern Light		Angle of Tow, deg	Remarks
	Angle, deg	Speed, fps	Angle, deg	Speed, fps		
	9.1	4.7	-2.3	5.8	25.5	Hit riverwall main lock
Sta 535	-17.7	3.5	-9.1	3.4	-15.7	Hit guard wall
Sta 695	-6.8	4.5	-2.3	6.9	-19.1	Hit guard wall
Sta 960	-11.3	4.0	0	4.5	-16.6	Hit guard wall
	-15.6	3.1	-15.6	3.8	0.6	Hit center wall existing lock
					-0.9	Hit upper end guide wall
Sta 796	-11.3	4.5	-2.3	4.0	-38	Hit guard wall
Sta 1171	-11.3	6.2	0	6.1	-10.7	Hit upstream end of guard wall
Sta 838	-6.6	3.4	0	3.7	18.8	Stern hit guard wall
Sta 312	-6.8	5.0	-15.6	5.2	-7.3	Hit guard wall
Sta 754	-4.6	5.0	0	8.3	11.4	Stern hit guard wall
Sta 810	-13.5	5.0	-2.3	3.8	1.7	Stern hit guard wall
Sta 1008	-4.6	3.2	-4.6	4.0	17.8	Stern hit guard wall
Sta 412	-11.3	5.5	-13.0	5.7	-8.1	Hit guard wall
Sta 834	-4.6	5.0	0	8.3	12.3	Stern hit guard wall
	2.3	5.7	-9.1	5.6	8.5	Hit main lock
	-2.3	3.5	-13.5	3.2	24.2	Hit main lock
Sta 410	-11.3	5.4	0	5.2	0.4	Hit guard wall
	-4.6	5.5	-6.8	5.7	4.4	Hit riverwall main lock
	-2.3	5.0	-2.3	5.3	2.5	Hit riverwall main lock
Sta 495	-17.7	3.9	-13.5	4.1	0.4	Hit guard wall
	0	4.0	-9.1	10.5	4.7	Hit center wall existing lock
	0	5.1	17.7	5.2	20.2	Stern hit upstream end of guard wall
	-15.6	3.0	-25.6	3.6	-0.2	Hit center wall existing lock
	2.3	4.6	-6.8	5.0	7.7	Hit riverwall main lock

Table A5
Five-Barge Tow Approaching Main Lock - 25,000-cfs Riverflow

Impact Area or Station	Bow Light		Stern Light		Angle of Tow, deg	Remarks
	Angle, deg	Speed, fps	Angle, deg	Speed, fps		
Sta 272	-6.8	0.8	-9.1	0.9	-5.8	Head landed on guard wall
Sta 272	-9.1	0.8	0	0.7	-6.4	Head landed on guard wall
Sta 247	0	2.6	0	2.6	-0.8	Head landed on guard wall
	0	1.3	0	1.3	-0.9	Entered riverward lock / no impact on wall
Sta 496	-4.6	0.7	-4.6	0.7	-7.0	Head landed on guard wall
	-0.9	0.9	0	0.8	-5.5	Entered riverward lock / no impact on wall
Sta 497	-4.6	0.9	-4.6	0.9	-7.1	Head landed on guard wall
Sta 471	-6.8	0.9	-2.3	0.9	-4.3	Head landed on guard wall
Sta 521	-9.1	0.7	-6.8	2.9	-6.7	Head landed on guard wall
Sta 446	-4.6	0.5	-6.8	0.5	-6.1	Head landed on guard wall
Sta 347	-19.8	0.8	-11.3	0.5	-10.3	Head landed on guard wall
Sta 471	-9.1	0.7	-11.3	0.7	-6.7	Head landed on guard wall
Sta 646	-5.7	0.8	-9.9	0.8	-6.5	Head landed on guard wall
	-0.9	0.4	0	0.4	-0.8	Entered riverward lock / no impact on wall
Sta 419	-6.8	0.7	-6.8	0.7	-5.3	Head landed on guard wall
	-1.0	1.0	0	0.9	-2.8	Entered riverward lock / no impact on wall
Sta 460	-9.1	1.0	-12.3	0.9	-6.8	Head landed on guard wall
Sta 298	-4.6	1.0	-6.8	1.0	-8.5	Head landed on guard wall
Sta 483	-11.3	1.0	-13.5	0.7	-10.2	Head landed on guard wall
Sta 696	-15.6	0.6	-6.8	0.7	-6.1	Head landed on guard wall
	-1.0	0.4	0	0.4	-3.6	Entered riverward lock / no impact on wall
Sta 272	-11.3	0.8	-9.1	0.8	-7.6	Head landed on guard wall
Sta 547	-6.8	1.3	-6.8	1.2	-7.8	Head landed on guard wall
Sta 472	-6.8	1.3	-11.3	1.1	-5.1	Head landed on guard wall
Sta 572	-6.8	1.6	-4.6	1.5	-7.3	Head landed on guard wall

Table A6
Processed Data - Nine-Barge String Driving into Main Chamber - 25,000-cfs Riverflow

		Bow Light		Stern Light				Computed Head Components to Wall			
Test	Impact Area or Station	Angle, deg	Speed ft/sec	Angle, deg	Speed ft/sec	Angle of Tow deg	Remarks	% error V ft/sec	Vn ft/sec	Vt ft/sec	∞ deg/sec
1	Sta 1583	4.6	3.7	4.6	3.4	3.1	Head landed on guide wall	-0.297	0.297	3.689	-0.005
2	Sta 1583	4.6	3.1	13.5	3.2	4.4	Head landed on guide wall	-0.017	0.244	3.084	0.058
3	Sta 1634	4.6	3.7	9.1	4	2.6	Head landed on guide wall	0.246	0.293	3.684	0.04
4	Sta 1487	2.3	2.8	13.5	2.7	7.1	Head landed on guide wall	-0.235	0.106	2.792	0.057
5	Sta 1536	0	2.7	4.6	2.4	6.7	Head landed on guide wall	-0.328	-0.001	2.698	0.018
6	Sta 1380	4.6	3.9	4.6	4.1	5.8	Head landed on guide wall	0.197	0.312	3.887	0.004
7	Sta 1132	0	3	2.3	3	4.5	Head landed on guide wall	-0.012	-0.001	2.999	0.014
8	Sta 1082	2.3	2.4	2.3	2.3	2.1	Head landed on guide wall	-0.1	0.096	2.396	-0.001
9	Sta 1085	2.3	2.5	0.5	2.8	4.2	Head landed on guide wall	0.307	0.101	2.499	-0.006
10	Sta 1098	6.8	3.8	4.6	4	3.8	Head landed on guide wall	0.222	0.451	3.775	-0.013
11	Sta 684	2.3	2.2	9.1	2.2	2.1	Head landed on guide wall	0.035	0.086	2.195	0.03
12	Sta 1484	2.3	1.8	0	2	7.5	Head landed on guide wall	0.209	0.073	1.799	-0.005
13	Sta 784	2.3	2.5	0	2.4	1	Head landed on guide wall	-0.096	0.101	2.499	-0.012
14	Sta 260	2.3	1.5	0	1.5	0.5	Head landed on guide wall	0.002	0.061	1.499	-0.007
15	Sta 735	-2.3	1.7	2.3	1.9	1.8	Head landed on guide wall	0.195	-0.07	1.697	0.017
16	Sta 1721	4.6	2.4	2.3	2.6	4.7	Head landed on guide wall	0.212	0.193	2.393	-0.008
17	Sta 1235	0.8	1.9	4.6	2	6.6	Head landed on guide wall	0.078	0.025	1.898	0.017
18	Sta 1207	-2.5	2.5	4.6	2.4	1.7	Head landed on guide wall	-0.114	-0.112	2.494	0.035
19	Sta 1160	2.3	1.9	0	1.8	5.1	Head landed on guide wall	-0.091	0.077	1.899	-0.01
20						1.1	Tow entered main lock/ no impact on walls				
21	Sta 1031	0	2.1	2.3	2.1	3.6	Head landed on guide wall	-0.007	-0.001	2.099	0.01
22	Sta 410	-2.3	2	0	2.5	2.3	Head landed on guide wall	0.498	-0.081	1.997	0.012
23	Sta 1534	2.3	1.7	2.3	1.6	4.3	Head landed on guide wall	-0.099	0.068	1.699	-0.001
24	Sta 586	9.1	1.9	0	1.9	1	Head landed on guide wall	0.029	0.304	1.879	-0.035
25	Sta 1561	0	2.3	0	1.9	4.7	Head landed on guide wall	-0.399	0	2.3	0.004
							AVERAGE	0.01813	0.109333	2.493833	0.008542
							STDEV	0.21657	0.142954	0.708224	0.02265
							MAX	0.498	0.451	3.887	0.058
							MIN	-0.399	-0.112	1.499	-0.035

Table A7
Processed Data - Nine-Barge String Flanking into Main Chamber - 106,000-cfs Riverflow

Test	Impact Area or Station	Bow Light		Stern Light		Angle of Tow deg	Remarks	Computed Head Components to Wall			
		Angle, deg	Speed ft/sec	Angle, deg	Speed ft/sec			% error Vn ft/sec	Vn ft/sec	Vt ft/sec	∞ deg/sec
1	Sta 1835	9.1	1.6	6.8	1.6	-3.4	Stern landed on guide wall	0.005	0.254	1.58	-0.006
2	Sta 1710	-2.3	0.9	13.5	0.6	-4.3	Stern landed on guide wall	-0.302	-0.038	0.898	0.019
3	Sta 1780	-26.6	2.2	34.2	3	-14	Stern landed on guide wall	1.145	-0.011	1.952	0.239
4	Sta 1810	-6.8	2	6.8	1.8	-3.6	Stern landed on guide wall	-0.17	-0.241	1.982	0.045
5	Sta 1604	13.5	1.9	9.1	0.8	-4.6	Stern landed on guide wall	-1.08	0.446	1.849	-0.022
6	Sta 1330	9.1	2.6	0	1.5	2.3	Head landed on guide wall	-1.05	0.415	2.571	-0.044
7	Sta 1811	-9.1	9.8	13.5	0.8	-3.2	Stern landed on guide wall	-8.788	-1.57	9.658	0.216
8	Sta 1310	11.3	2.4	-6.8	2.3	2.6	Head landed on guide wall	-0.036	0.476	2.36	-0.072
9	Sta 1859	6.8	1.8	-6.8	1.6	-0.4	Stern landed on guide wall	-0.201	0.217	1.791	-0.039
10	Sta 1561	4.6	1.9	0	1.9	-4	Stern landed on guide wall	-0.005	0.154	1.895	-0.015
11	Sta 1454	2.3	2.7	-2.3	2.5	3.2	Head landed on guide wall	-0.188	0.11	2.7	-0.021
12	Sta 360	2.3	2.6	-6.6	3.3	6	Head landed on guide wall	0.727	0.108	2.602	-0.04
13	Sta 1610	4.6	2.8	-6.8	2.6	3.3	Head landed on guide wall	-0.178	0.229	2.796	-0.053
14	Sta 1835	-9.1	1	0	1.6	-1.1	Stern landed on guide wall	0.616	-0.159	0.986	0.014
15	Sta 1260	4.6	2.7	0	2.6	2.4	Head landed on guide wall	-0.082	0.218	2.693	-0.021
16	Sta 1800	4.6	1.4	2.23	1.4	-0.2	Stern landed on guide wall	0.003	0.113	1.396	-0.006
17	Sta 1510	27.5	1.8	-15.6	1.6	1.7	Head landed on guide wall	-0.018	0.842	1.608	-0.122
18	Sta 1585	23.7	1.3	-23.7	1.3	2.2	Head landed on guide wall	0.04	0.531	1.2	-0.101
19	Sta 1360	11.3	2.2	-6.8	2.2	2.1	Head landed on guide wall	0.052	0.437	2.164	-0.067
20	Sta 1780	-6.8	1.4	4.68	1.6	-0.6	Stern landed on guide wall	0.208	-0.168	1.388	0.029
21	Sta 1535	17.7	2.8	-22.2	2.5	1.7	Head landed on guide wall	-0.299	0.867	2.684	-0.175
22	Sta 1585	-15.6	2	11.3	2	-2.1	Stern landed on guide wall	0.069	-0.546	1.919	0.09
23	Sta 1433	31	1.7	-15.6	1.5	2.5	Head landed on guide wall	0.043	0.886	1.469	-0.124
24	Sta 1909	4.6	2.1	4.6	2.1	-0.9	Stern landed on guide wall	0	0.168	2.093	0
25	Sta 1435	17.7	1.7	-6.8	1.6	1.9	Head landed on guide wall	-0.007	0.523	1.626	-0.069
							AVERAGE	-0.37984	0.13044	2.2344	-0.0138
							STDEV	1.808423	0.553875	1.641357	0.092554
							MAX	1.145	0.886	9.658	0.239
							MIN	-8.788	-1.57	0.898	-0.175

Table A8
Processed Data - Nine-Barge String Approaching Main Chamber - Loss of Power - 50,000-cfs Riverflow

Test	Impact Area or Station	Bow Light Angle, deg	Bow Light Speed ft/sec	Stern Light Angle, deg	Stern Light Speed ft/sec	Angle of Tow deg	Remarks	Computed Head Components to Wall: % error V ft/sec	Vn ft/sec	Vt ft/sec	∞ deg/sec
1	Sta 649	-6.8	3.8	-6.8	3.4	-13.7	Hit guard wall	-0.375	-0.452	3.772	0.021
2		-9.5	2.8	-2.3	5	-7.7	Hit center wall existing locks	2.249	-0.462	2.762	-0.008
3		-6.8	2.1	0	2.2	-11.8	Hit riverwall main lock	0.163	-0.252	2.083	0.033
4		9.1	4.2	2.3	4.2	9.1	Hit main lock chamber	0.127	0.67	4.155	-0.073
5		0	3.8	-6.8	3.5	-0.4	Hit riverwall main lock	-0.328	0.006	3.806	-0.062
6		6.8	1.8	2.3	1.7	4.4	Hit main lock chamber	-0.077	0.215	1.79	-0.023
7		-6.8	2.8	-2.3	2.9	-2	Hit riverwall main lock	0.125	-0.334	2.778	0.032
8		-13.5	2.5	10	2.5	-6.2	Hit riverwall main lock	0.141	-0.599	2.419	0.152
9		-4.6	2	-6.8	2.1	-1	Hit riverwall main lock	0.09	-0.159	1.995	-0.014
10	Sta 310	-8.1	2.6	-11.3	2.5	-11.7	Hit guard wall	-0.145	-0.365	2.575	-0.014
11		-11.3	2.6	-11.3	2.7	-14.6	Hit center wall existing locks	0.09	-0.509	2.55	-0.007
12		-4.6	2.7	-6.8	3.2	-15.9	Hit center wall existing locks	0.423	-0.212	2.694	-0.044
13		-6.8	2.6	-6.8	2.7	-6.4	Hit center wall existing locks	0.097	-0.308	2.582	-0.003
14		-9.1	2.1	-4.6	2.1	-3.1	Hit riverwall main lock	0.028	-0.334	2.071	0.024
15		-5.2	1.1	0	1.1	-2.6	Hit riverwall main lock	0.009	-0.101	1.094	0.015
16	Sta 587	-13.5	3.1	-11.3	2.7	-8.7	Hit guard wall	-0.333	-0.727	3.012	0.037
17	Sta 661	-13.5	2	-11.3	2.6	-9.4	Hit guard wall	0.059	-0.465	1.946	-0.021
18		6.8	2.7	-2.3	2.8	6.2	Hit riverwall main lock	0.163	0.325	2.687	-0.063
19	Sta 941	2.3	0.3	4.6	2.6	6.7	Hit guide wall main lock	2.253	0.007	0.293	0.07
20		-6.8	2.9	-4.6	2.8	-3.7	Hit riverwall main lock	-0.081	-0.345	2.878	0.019
21		-2.3	2.6	-4.6	2.6	-2.9	Hit riverwall main lock	-0.012	-0.103	2.599	-0.016
22		-3.5	2.3	-3.6	2.5	-3.7	Hit riverwall main lock	0.198	-0.14	2.296	-0.004
23		-0.1	0.8	0	0.9	-0.2	Entered main lock chamber	0.1	-0.001	0.8	0
24		0	1	0	1	-0.3	Entered main lock chamber	0	0	1	0
25		1	4.2	0.9	4.2	1	Hit upstream end of main lock guide wall	0	0.073	4.199	-0.001
							AVERAGE	0.1986	-0.18288	2.43344	0.00208
							STDEV	0.6424	0.309219	0.977807	0.045547
							MAX	2.253	0.67	4.199	0.152
							MIN	-0.375	-0.727	0.293	-0.073

Table A9
Processed Data - Nine-Barge String Approaching Main Lock - Loss of Power - 125,000-cfs Riverflow

Test	Impact Area or Station	Bow Light		Stern Light		Angle of Tow deg	Remarks	Computed Head Components to Wall			
		Angle, deg	Speed ft/sec	Angle, deg	Speed ft/sec			% error Vn ft/sec	Vn ft/sec	Vt ft/sec	ω deg/sec
1		9.1	4.7	-2.3	5.8	25.5	Hit riverwall main lock	1.462	0.745	4.645	-0.037
2	Sta 535	-17.7	3.5	-9.1	3.4	-15.7	Hit guard wall	0.164	-1.069	3.331	0.048
3	Sta 695	-6.8	4.5	-2.3	6.9	-19.1	Hit guard wall	2.376	-0.527	4.471	-0.053
4	Sta 960	-11.3	4	0	4.5	-16.6	Hit guard wall	0.777	-0.79	3.919	0.056
5		-15.6	3.1	-15.6	3.8	0.6	Hit center wall existing lock	0.676	-0.832	2.987	-0.017
6						-0.9	Hit upper end guide wall				
7	Sta 796	-11.3	4.5	-2.3	4	-38	Hit guard wall	0.116	-0.892	4.412	0.079
8	Sta 1171	-11.3	6.2	0	6.1	-10.7	Hit upstream end of guard wall	0.245	-1.227	6.072	0.113
9	Sta 838	-6.6	3.4	0	3.7	18.8	Stern hit guard wall	0.179	-0.393	3.372	0.045
10	Sta 312	-6.8	5	-15.6	5.2	-7.3	Hit guard wall	0.296	-0.611	4.95	0.188
11	Sta 754	-4.6	5	0	8.3	11.4	Stern hit guard wall	3.171	-0.408	4.973	0.1
12	Sta 810	-13.5	5	-2.3	3.8	1.7	Stern hit guard wall	-1.095	-1.175	4.853	0.094
13	Sta 1008	-4.6	3.2	-4.6	4	17.8	Stern hit guard wall	0.779	-0.258	3.188	0.017
14	Sta 412	-11.3	5.5	-13	5.7	-8.1	Hit guard wall	0.13	-1.076	5.395	-0.021
15	Sta 834	-4.6	5	0	8.3	12.3	Stern hit guard wall	3.155	-0.408	4.973	0.105
16		2.3	5.7	-9.1	5.6	8.5	Hit main lock	0.001	0.237	5.706	-0.107
17		-2.3	3.5	-13.5	3.2	24.2	Hit main lock	-0.103	-0.137	3.505	-0.068
18	Sta 410	-11.3	5.4	0	5.2	0.4	Hit guard wall	-0.103	-1.067	5.286	0.101
19		-4.6	5.5	-6.8	5.7	4.4	Hit riverwall main lock	0.195	-0.439	5.484	-0.021
20		-2.3	5	-2.3	5.3	2.5	Hit riverwall main lock	0.3	-0.201	4.996	0
21	Sta 495	-17.7	3.9	-13.5	4.1	0.4	Hit guard wall	0.27	-1.188	3.713	0.022
22		0	4	-9.1	10.5	4.7	Hit center wall existing lock	6.483	0.009	4.01	-0.108
23		0	5.1	17.7	5.2	20.2	Stern hit upstream end of guard wall	-0.683	-0.007	5.084	0.137
24		-15.6	3	-25.6	3.6	-0.2	Hit center wall existing lock	0.354	-0.8	2.896	-0.071
25		2.3	4.6	-6.8	5	7.7	Hit riverwall main lock	0.469	0.19	4.603	-0.069
							AVERAGE	0.81725	-0.5135	4.451	0.022208
							STDEV	1.58703	0.521888	0.910477	0.081421
							MAX	6.483	0.745	6.072	0.188
							MIN	-1.095	-1.227	2.896	-0.108

Table A10
Processed Data - Five-Barge String Driving into Existing Lock -25,000-cfs Riverflow

		Bow Light		Stern Light				Computed Head Components to Wall			
Test	Impact Area or Station	Angle, deg	Speed ft/sec	Angle, deg	Speed ft/sec	Angle of Tow deg	Remarks	% error V ft/sec	Vn ft/sec	Vt ft/sec	∞ deg/sec
1	Sta 272	-6.8	0.8	-9.1	0.9	-5.8	Head landed on guard wall	0.089	-0.094	0.795	-0.006
2	Sta 272	-9.1	0.8	0	0.7	-6.4	Head landed on guard wall	-0.075	-0.128	0.789	0.015
3	Sta 247	0	2.6	0	2.6	-0.8	Head landed on guard wall	0	0	2.6	0
4		0	1.3	0	1.3	-0.9	Entered riverward lock/no impact on wall	0	0	1.3	0
5	Sta 496	-4.6	0.7	-4.6	0.7	-7	Head landed on guard wall	0	-0.056	0.698	0
6		-0.9	0.9	0	0.8	-5.5	Entered riverward lock/no impact on wall	-0.098	-0.014	0.9	0.003
7	Sta 497	-4.6	0.9	-4.6	0.9	-7.1	Head landed on guard wall	0	-0.072	0.897	0
8	Sta 471	-6.8	0.9	-2.3	0.9	-4.3	Head landed on guard wall	0.011	-0.107	0.893	0.008
9	Sta 521	-9.1	0.7	-6.8	2.9	-6.7	Head landed on guard wall	2.146	-0.105	0.696	-0.055
10	Sta 446	-4.6	0.5	-6.8	0.5	-6.1	Head landed on guard wall	-0.004	-0.04	0.499	-0.002
11	Sta 347	-19.8	0.8	-11.3	0.5	-10.3	Head landed on guard wall	-0.227	-0.274	0.751	0.025
12	Sta 471	-9.1	0.7	-11.3	0.7	-6.7	Head landed on guard wall	-0.008	-0.11	0.691	-0.003
13	Sta 646	-5.7	0.8	-9.9	0.8	-6.5	Head landed on guard wall	-0.014	-0.079	0.797	-0.006
14		-0.9	0.4	0	0.4	-0.8	Entered riverward lock/no impact on wall	0	-0.006	0.4	0.001
15	Sta 419	-6.8	0.7	-6.8	0.7	-5.3	Head landed on guard wall	0	-0.083	0.695	0
16		-1	1	0	0.9	-2.8	Entered riverward lock/no impact on wall	-0.099	-0.018	1	0.003
17	Sta 460	-9.1	1	-12.3	0.9	-6.8	Head landed on guard wall	-0.111	-0.158	0.988	-0.002
18	Sta 298	-4.6	1	-6.8	1	-8.5	Head landed on guard wall	-0.009	-0.08	0.997	-0.004
19	Sta 483	-11.3	1	-13.5	0.7	-10.2	Head landed on guard wall	-0.289	-0.197	0.98	0.01
20	Sta 696	-15.6	0.6	-6.8	0.7	-6.1	Head landed on guard wall	0.125	-0.162	0.577	0.007
21		-1	0.4	0	0.4	-3.6	Entered riverward lock/no impact on wall	0	-0.007	0.4	0.001
22	Sta 272	-11.3	0.8	-9.1	0.8	-7.6	Head landed on guard wall	0.009	-0.157	0.784	0.003
23	Sta 547	-6.8	1.3	-6.8	1.2	-7.8	Head landed on guard wall	-0.097	-0.154	1.291	0.003
24	Sta 472	-6.8	1.3	-11.3	1.1	-5.1	Head landed on guard wall	-0.217	-0.153	1.291	-0.005
25	Sta 572	-6.8	1.6	-4.6	1.5	-7.3	Head landed on guard wall	-0.084	-0.19	1.588	0.009
							AVERAGE	0.04192	-0.09776	0.93188	0.0002
							STDEV	0.44821	0.0718478	0.449081	0.013441
							MAX	2.146	0	2.6	0.025
							MIN	-0.289	-0.274	0.4	-0.055

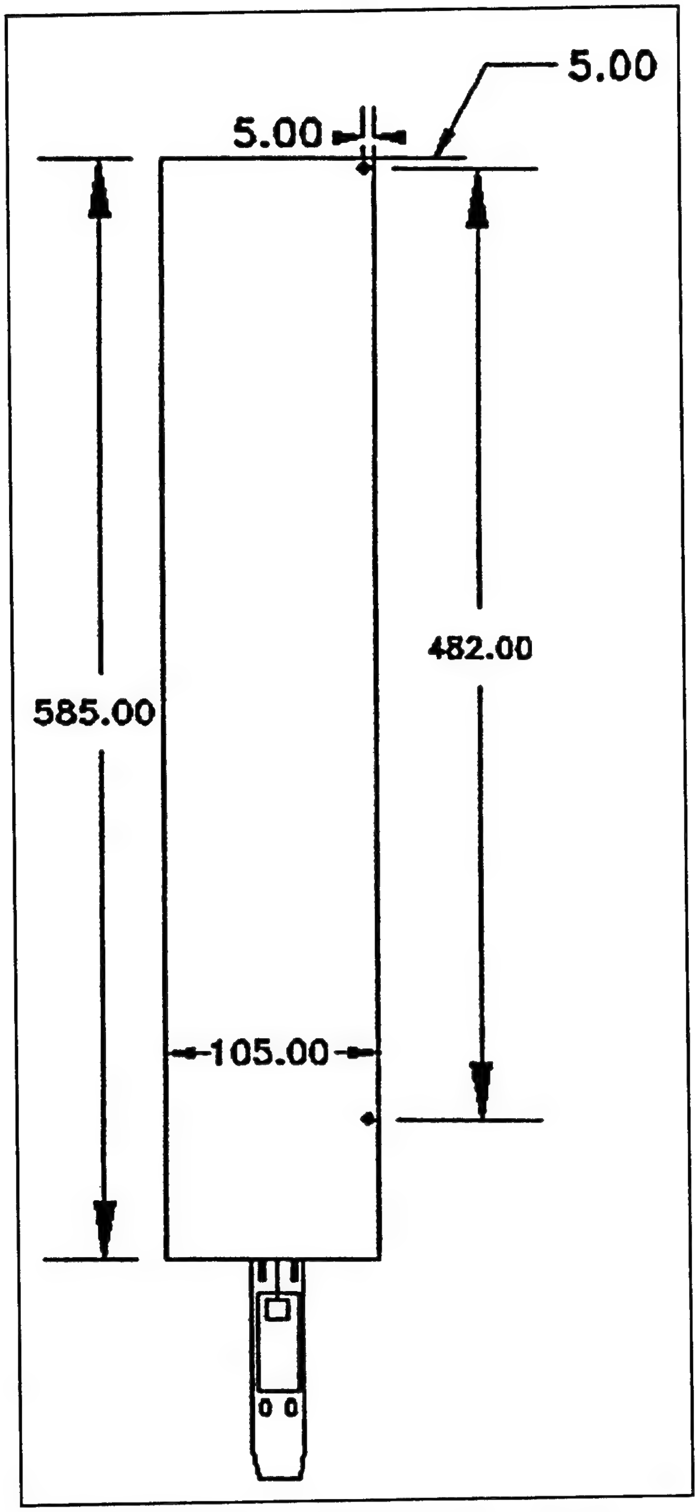

Figure A1. Lights on nine-barge string driving into main lock - 25,000-cfs riverflow

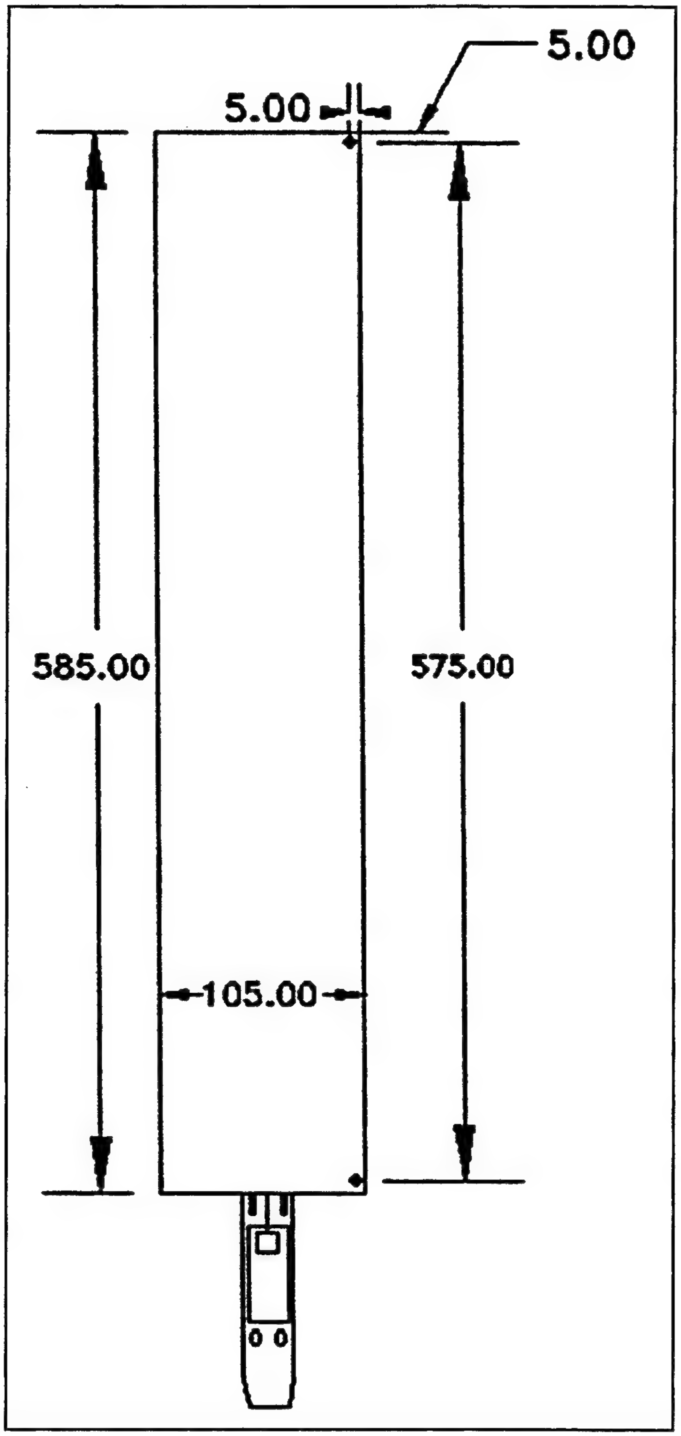

Figure A2. Lights on nine-barge string flanking into main chamber - 106,000-cfs riverflow

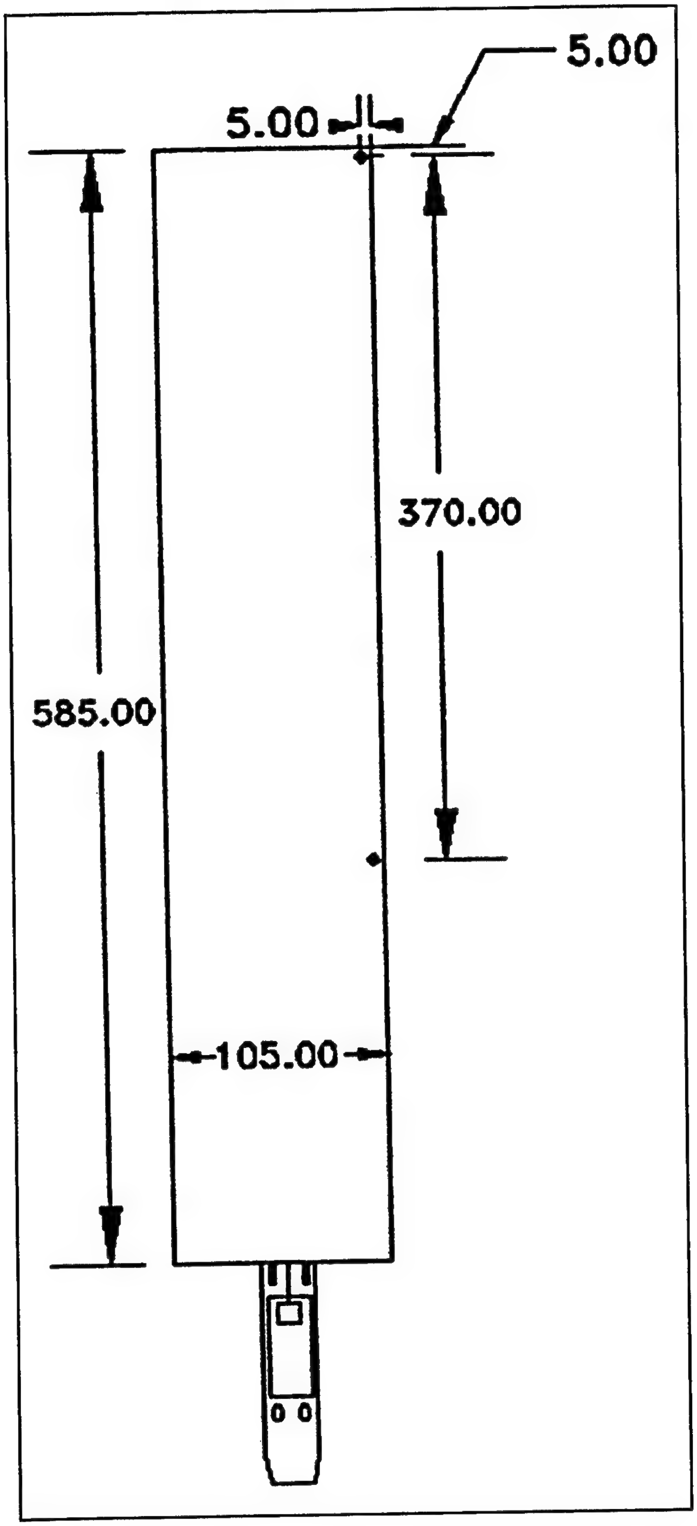

Figure A3. Lights on nine-barge string - loss of power - 50,000-cfs riverflow

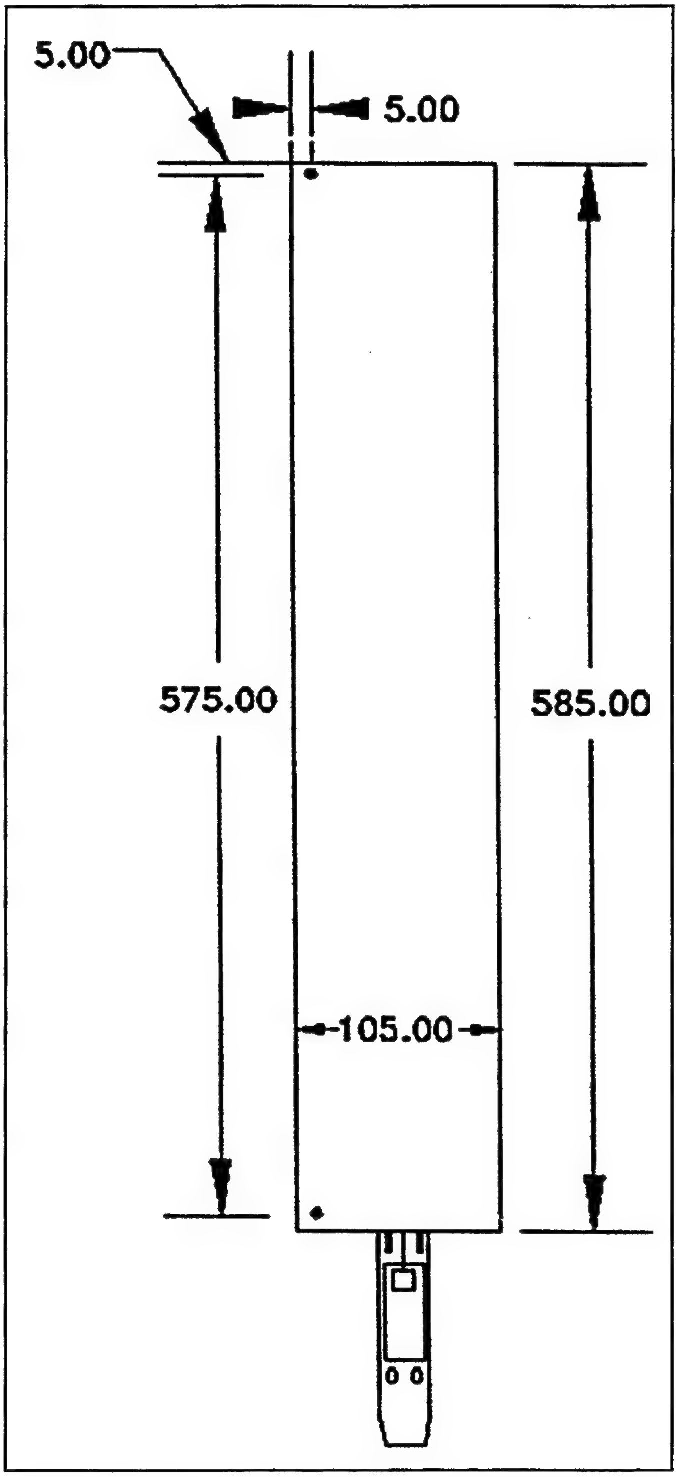

Figure A4. Lights on nine-barge string - loss of power - 125,000-cfs riverflow

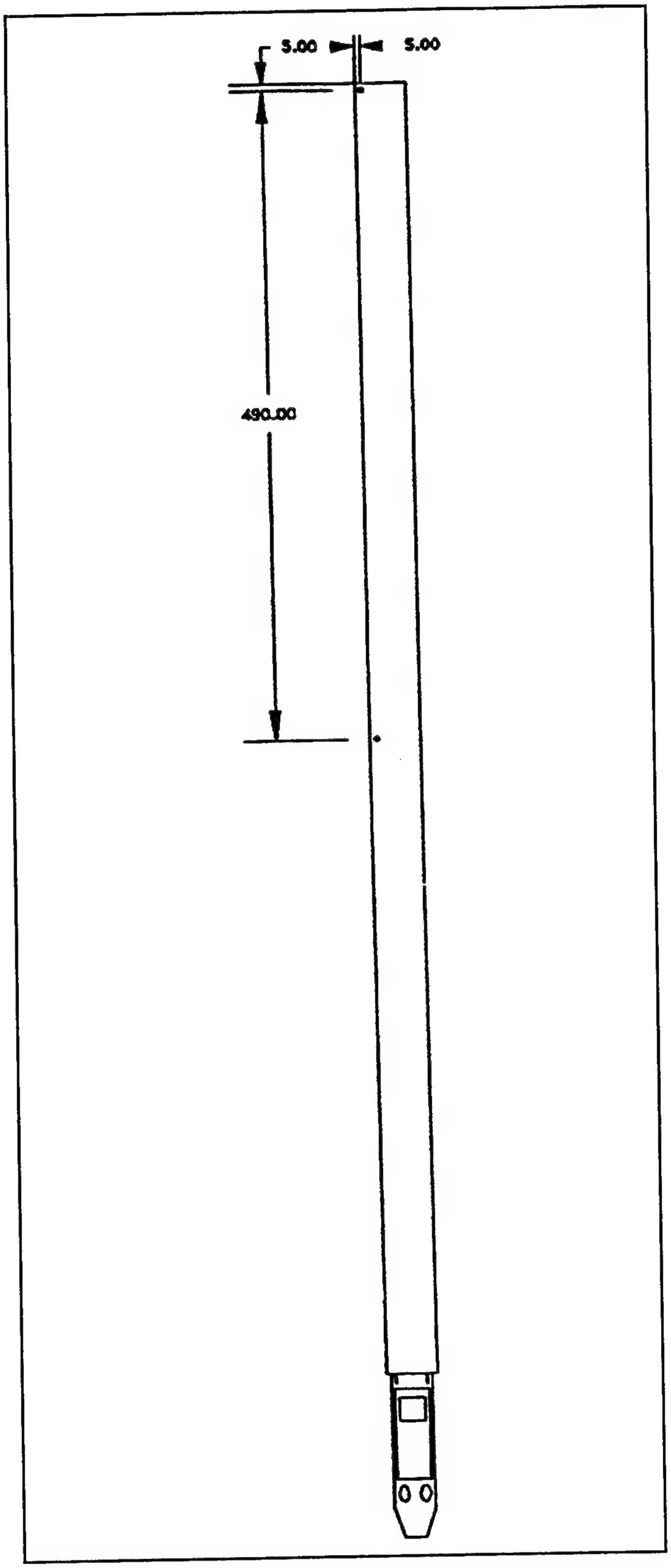

Figure A5. Lights on five-barge string driving into existing chambers - 25,000-cfs riverflow

Appendix B
Sample Calculation of PBIA Model

Marmet Lock and Dam

Upper Guard Wall Probabilistic Analysis

(Maintence Condition - 1 X 5 Jumbo String only)

Jumbo Barges (195 x 35) 195 35 1500

No. of barges	pdf	cdf
0	0.000	0.000
1	0.005	0.005
2	0.01	0.015
3	0.02	0.035
4	0.165	0.2
5	0.8	1
6	0	1
7	0	1
8	0	1
9	0	1
10	0	1
11	0	1
Total	1	

	Length (ft)	Width (ft)	Displacement (short tons)
0	195	35	1500
1	195	35	1500
2	390	35	3000
3	585	35	4500
4	780	35	6000
5	975	35	7500
6	585	70	9000
7	585	105	10500
8	585	105	12000
9	585	105	13500
10	780	105	15000
11	780	105	16500
11+	780	105	16500

Random Variables

Type of barge (Jumbo/Std)	jumbo	
Number of Barges	5	
Length of tow, L =	975	ft
Beam of tow, B=	35	ft
Speed of Tow, Vn =	0.24	ft/s
Speed of Tow, Vt =	0.86	ft/s
Displacement of tow, W =	7500	short tons
Collison Angle, Ang =	6.92	degrees
Normal Stiffness of Flexible Wall, K1 =	24988.29	kips/ft
Weight of struck wall, W1	1476.77	kips
Mass of struck wall, M1 =	45.89948	k-sec2/ft

θ = 0.120777 radians

Figure B1. Sample calculation of PBIA model (Sheet 1 of 3)

Constants

Effective thickness of barge hull, teff =	1.17	in
Dynamic coefficient of friction, Mu =	0.176	
Minorsky Pressure, P =	13.7	ksi
Gravitational Constant, g =	32.174	ft2/sec
Added mass for structure structure =	1.4	
Added mass fraction in longitudinal direction	0.05	
Added mass fraction in transverse direction	0.4	
Added inertial fraction	0.4	

Calculations

M1y =	64.2592777			
M =	466.214956			
Mx =	489.525704			
My =	652.700939			
Mnorm =	649.557892			
Mtan =	491.308693			
I =	36980558.8			
I θ=	51772782.4	0		
Vn =	0.24	0		
Vt =	0.86			
R =	487.814001			
α =	0.03588203			
K2 =	1608.18437		β1 =	413.8931
ω1 =	20.3480636		β2 =	2.475814
ω2 =	1.52488204		β12 =	208.1845
			η2 =	42378.02
			η =	205.8592

Intermediate Terms

Rotational DOF

λ1 =	-0.00602
λ2 =	16.44529
Sθ =	0.295201
Cθ =	0.97151
Q =	-468.445
D1 =	-5.2E-07
D2 =	-0.00141
A1 =	0.014925
A2 =	0.904732
A3 =	-0.67966

Figure B1. (Sheet 2 of 3)

Axial DOF

S1 =	0.000421
S2 =	0.343074
S3 =	-0.39348
S4 =	0.634995

Numerical Solution of Roots (Use linear interpolation method)

Xo =	0.403764	sec
T =	0.45628	sec

Solutions for T

Tfinal =	0.45628	sec
	0.45628	

Striking Object

y(T) =	0.100847	feet
x(T) =	0.409211	feet
θ(T) =	-5.1E-05	deg/sec
v(T) =	0.18406	ft/sec
u(T) =	0.848623	ft/sec
ω(T) =	-0.01878	deg/sec

Struck Object

yn(T) =	0.076201	feet	yrot(T) =	-0.02465
vn(T) =	0.025347	feet/sec	vrot(T)=	-0.15871
y1(T) =	0.006032	feet		
v1(T) =	0.025643	feet/sec		
yn(T) - y1(T)	0.070169	feet		

Normal Force on Striking Object

Fmax(T) = 112.844

Normal Force on Struck Object

F1max(T) = 150.7275

Figure B1. (Sheet 3 of 3)

Appendix C
Stiffness Calculations for Foundation

Marmet Lock and Dam
Upper Guard Wall

Stiffness Calculations

Drilled Shaft Parameters
(assume soil adds no resistance)

Diameter of shaft =	7	ft	
Length of shaft =	25	ft	(moved up 2 ft to approx. soil/rock stiffness/rotations)
Moment of Inertia of shaft =	2443920.3	in^4	

Material Properties

Unit weight of concrete =	150	pcf
Compressive Strength =	4000	psi
Modulus of Elasticity(ACI) =	3834253.5	psi

Fixed-Fixed (3EI/L^3)

Stiffness per shaft, k	1041178.9	lb/in
	1041.1789	k/in
	12494.147	k/ft
Combined Stiffness, k	24988.294	k/ft

Fixed-Pinned (12EI/L^3)

Stiffness per shaft, k	4164715.6	lb/in
	4164.7156	k/in
	49976.587	k/ft
Combined Stiffness, k	99953.174	k/ft

Weight Calculations

Unit weight of concrete =	150	pcf
Gravitational constant, g =	32.17	ft/sec^2

Figure C1. Stiffness calculation for drilled shaft/post-tensioned box beam at Marmet Locks (Sheet 1 of 3)

Results				% of Total weight
Total Weight of Cap =	1136768.8	lbs	1136.769 k	0.7697682
Mass of Cap =	35.34	k-sec2/ft		
Total Weight of Shafts =	339998.86	lbs	340.00 k	0.2302318
Mass of Shafts =	10.57	k-sec2/ft		
Total Wt. of Shafts and Cap =	1476767.6	lbs	1476.77 k	
Mass of Cap and Shaft =	45.91	k-sec2/ft		

Precast concrete cap

Length =	30	ft
Width =	8	ft
Height =	11	ft
Volume =	2640	ft^3
Weight =	396000	lbs

Thrust/Stop Block

Length =	13.5	ft
Height =	6	ft
Distance to slope =	6.75	ft
Toe height =	1	ft
Area1 =	13.5	ft^2
Area2 =	40.5	ft^2
Area3 =	20.25	ft^2
Total Area =	74.25	ft^2
Volume =	594	ft^3
Weight =	89100	lbs

Precast Concrete Beam

Length between segments =	105	ft	
1/2 span =	52.5	ft	
Area gross =	100	ft^2	
Area hollow =	47.5	ft^2	
Area Net =	52.5	ft^2	
Volume =	5512.5	ft^3	
Weight (Two 1/2 beams) =	826875	lbs	826.88 k
Height of water =	2.89	ft	
Unit Weight of water =	62.5	pcf	
Pressure =	1806.25	lbs/ft	
Uplift Force (97 ft length) =	175206.25	lbs	
Total Weight =	651668.75	lbs	651.6688 k

Figure C1. (Sheet 2 of 3)

Drilled Shafts

8 ft Section

Diameter =	8	ft
Length =	8	ft
Area =	50.27	ft^2
Volume =	402.12	ft^3
Weight =	60318.579	lbs

7 ft Section

Diameter =	7	ft
Length =	19	ft
Area =	38.48	ft^2
Volume =	731.21	ft^3
Weight =	109680.85	lbs

Total Weight - Shafts

Number of Shafts	2	
Total Weight =	339998.86	lbs

Figure C1. (Sheet 3 of 3)

Appendix D
Example Simulation Data for Guide Wall

The following data were extracted from the Monte Carlo Simulations for the PBIA of the upper guide wall at Marmet Locks to show examples of barge impact load value for the extreme load case and return periods.

Midspan Upper Guide Wall - Marmet Locks and Dam					
Example	Mass, kips	V_n, ft/s	V_t, ft/s	Angle, deg	Force, kips
1	16,823	0.66	3.24	1	710.3
2	17,487	0.81	1.88	1.7	710.7
3	16,920	0.78	3.8	3.1	709.2
4	17,297	0.87	2.01	4.9	710.7
5	16,856	1.07	5.8	8	710.4

Foundation Upper Guide Wall - Marmet Locks and Dam					
Example	Mass, kips	V_n, ft/s	V_t, ft/s	Angle, deg	Force, kips
1	16,802	0.807	4.01	3.98	810.2
2	16,401	0.602	3.03	1.98	810.3
3	17,129	0.851	2.52	4.94	810.6
4	17,608	0.962	5.41	6.91	810.7
5	16,354	0.544	3.22	1.5	810.1

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13. ABSTRACT *(Maximum 200 words)*

This report describes the probabilistic barge impact analysis for the upper guide and guard walls at Marmet Locks and Dam. The report covers the results from the scale model experiments and the statistical processing of experimental data. Tow distributions are developed for the improved fleet at Marmet Locks. Probabilistic barge impact analysis is performed for both the foundation supports and the precast concrete beams of the upper approach walls. Return periods for barge impact loads are developed for usual, unusual, and extreme load cases.

14. SUBJECT TERMS

Barge impact	Probabilistic
Foundation	Return period
Guard walls	Scale model experiments
Guide walls	Statistics
Impact angles	Tow distribution
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